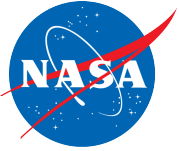


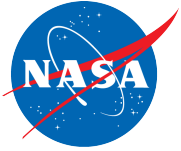
J.S. Haase, Y. Bock, J. Geng, A. Moore, G. Offield, M. Squibb, I. Small,
S. Gutman, J. Laber, E. Yu, R. Clayton, S. Kedar

Scripps Institution of Oceanography
Jet Propulsion Laboratory, NOAA National Weather Service, Caltech **ESTO**
Earth Science Technology Office **AIST-11-0072**



Objectives

- *Background:* Extensive existing permanent Global Positioning System (GPS) receiver sites for tectonic plate motion monitoring
- *Objective:* Enhance capabilities to transform sites into a sensor web that provides real-time information to users for rapid response to natural hazards.
- *Impact:* To better forecast, assess, and mitigate risk for natural hazards, including earthquakes, tsunamis, and extreme storms and flash flooding to save lives and reduce damage to critical infrastructure.
- *Approach:* develop and deploy SIO Geodetic Modules to network additional complementary sensors; demonstrate advanced geophysical warning products; transfer technology to partner agencies.
- *Key to success:* User driven₂ implementation



Data fusion: enhance GPS technology with low-cost sensors to mitigate risk for natural hazards



*GPS
Permanent station*

*Note: GPS =>
GNSS*

+

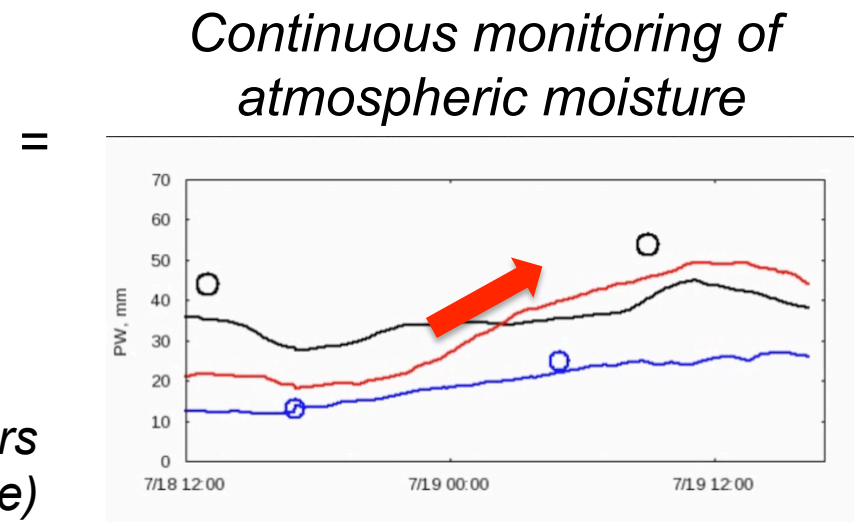
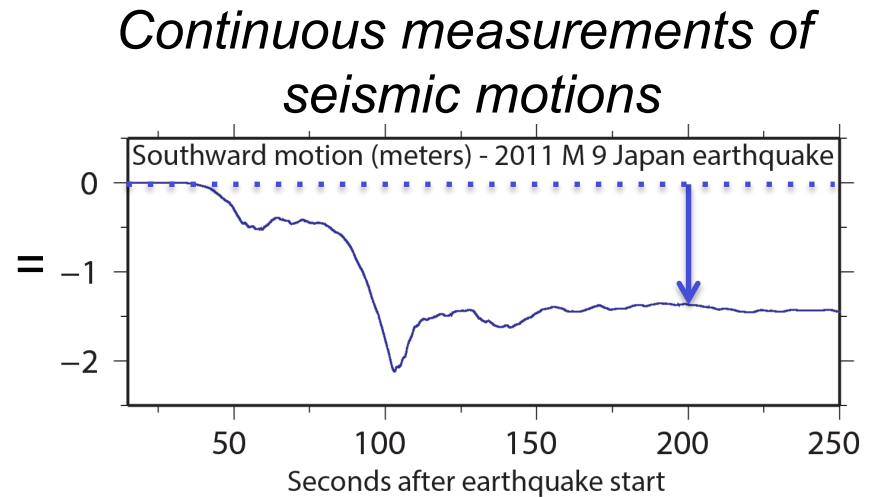


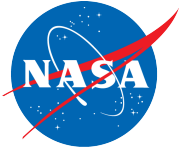
Accelerometer

+



*Meteorological Sensors
(pressure, temperature)*





User-driven implementation with AIST demonstration partners

Demonstration partners



GPS

+



Accelerometer

+



Meteorological Sensors
(pressure, temperature)

Earthquake hazard
products



CISN California Integrated Seismic Network
California's Partner to the **ANSS** *Advanced National Seismic System*
Earthquake seismology archive

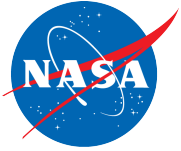
Severe weather
hazard products



NOAA **Earth System Research Laboratory**
Ground-Based GPS Meteorology



NATIONAL WEATHER SERVICE
National Weather Service Forecast Office
Los Angeles/Oxnard
National Weather Service Forecast Office
San Diego, CA



User-driven implementation: Evolving requirements for expanded user base

Demonstration partners

Seismic Early Warning



GPS

+
Accelerometer



+



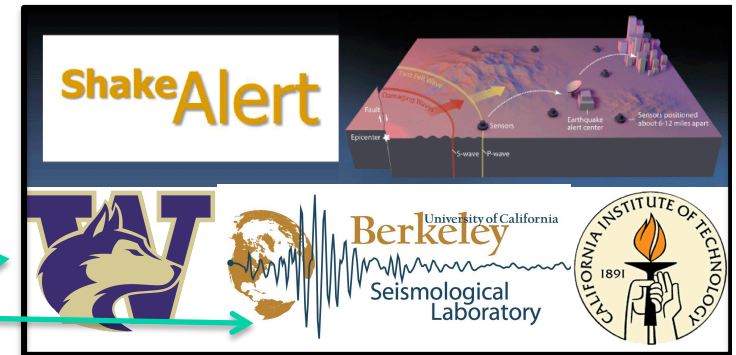
Meteorological Sensors
(pressure, temperature)

CISN California Integrated Seismic Network
California's Partner to the **ANSS** Advanced National Seismic System

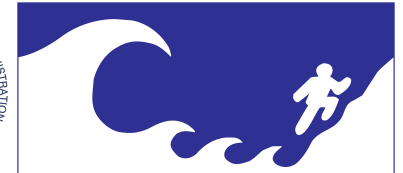
Earthquake hazard products
Tsunami hazard products
Structural monitoring products

NEES

Severe weather hazard products



Alaska and Pacific Tsunami Warning Centers



TSUNAMI!



National Weather Service Forecast Office

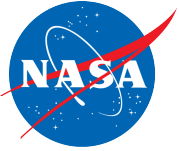
Los Angeles/Oxnard

National Weather Service Forecast Office

San Diego, CA

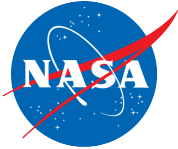
NOAA Earth System Research Laboratory
Ground-Based GPS Meteorology

ESTO
Earth Science Technology Office



Project Phases

- Develop a power-efficient, low-cost, plug-in Geodetic Module to interface with MEMS accelerometer, met sensors, and other low-cost instruments (e.g. gyroscope)
- Generate on-the-fly millimeter-level ground motions and precipitable water from the geodetic module
- Develop a real-time autonomous sensor web to transmit and receive information among regional nodes, including directly to users
- Transfer capabilities to users as part of a technology infusion, for decision support and rapid response to earthquakes, tsunamis, severe storms and flash flooding



Motivation for Earthquake Hazard Technology Demonstration

M 7.9 at 9 min

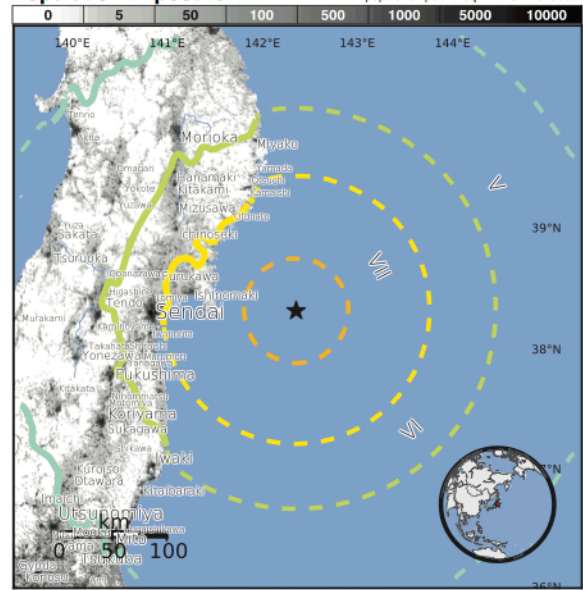
M 8.9 at 2.5 hrs

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)	--*	--*	3,227k*	6,192k	2,918k	719k	0	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures: none Vulnerable Structures: none	Resistant Structures: none Vulnerable Structures: none	Resistant Structures: none Vulnerable Structures: none	Resistant Structures: V. Light Vulnerable Structures: Light	Resistant Structures: Light Vulnerable Structures: Moderate	Resistant Structures: Moderate Vulnerable Structures: Moderate/Heavy	Resistant Structures: Moderate/Heavy Vulnerable Structures: Heavy	Resistant Structures: Heavy Vulnerable Structures: V. Heavy	Resistant Structures: V. Heavy Vulnerable Structures: V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure



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Date (UTC)	Dist. (km)	Mag.	Max MMI(1/4)	Shaking	Deaths
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1983-05-26	369	7.7	VII(174k)	104	104

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides, and fires that might have contributed to losses.

Selected City Exposure

MMI City	Population
VII Ishinomaki	117k
VII Yamato	32k
VII Shiogama	60k
VII Kogota	20k
VII Rifu	35k
VII Ofunato	35k
VI Sendai	1,038k
VI Yamagata	255k
V Morioka	295k
V Fukushima	294k
IV Utsunomiya	450k

bold cities appear on map

(k = x1000)

Event ID: usc0001xgp

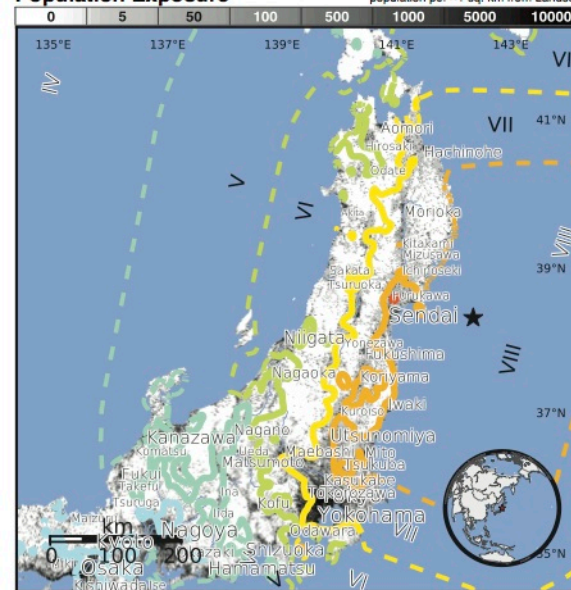
PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty. <http://earthquake.usgs.gov/pager>

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VII Yokohama	3,574k
IV Nagoya	2,191k
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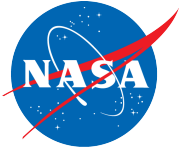
bold cities appear on map

(k = x1000)

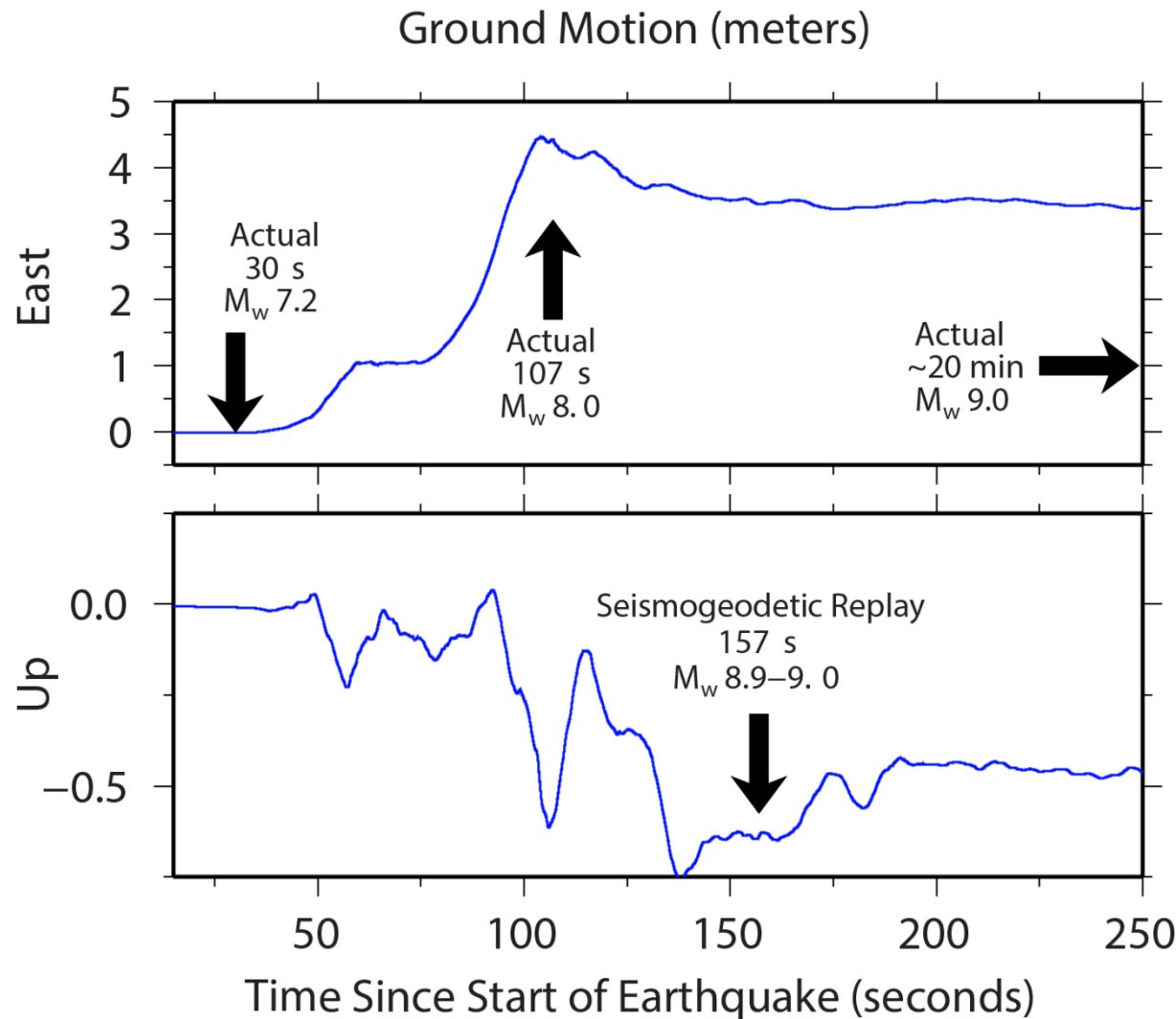
Event ID: usc0001xgp

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2011 Mw 9.0 Tohoku-oki earthquake was underestimated by traditional seismic methods

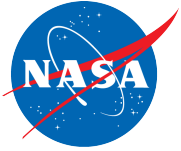


GPS + accelerometer sensors = seismogeodetic waveforms



Permanent displacement is DIRECTLY related to size of rupture and slip on fault, therefore earthquake size

Our system improves on traditional seismic monitoring by estimating ground acceleration **and permanent displacements**



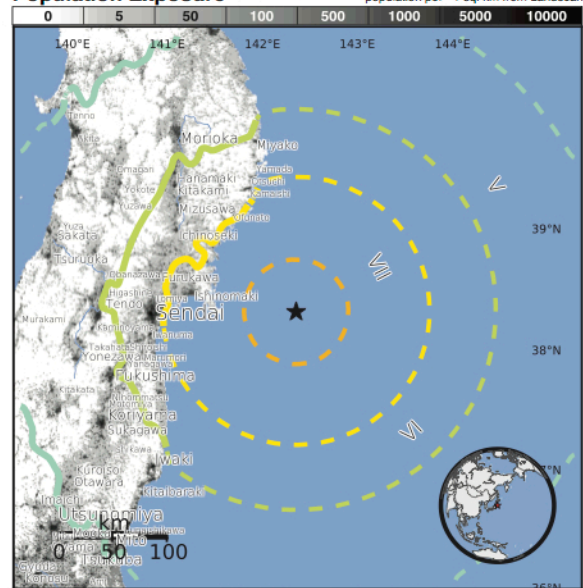
Technology Demonstration – Earthquake and Tsunami Hazards

M 7.9 at 9 min
Traditional seismic – point source

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POTENTIAL DAMAGE									
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*Estimated exposure only includes population within the map area.

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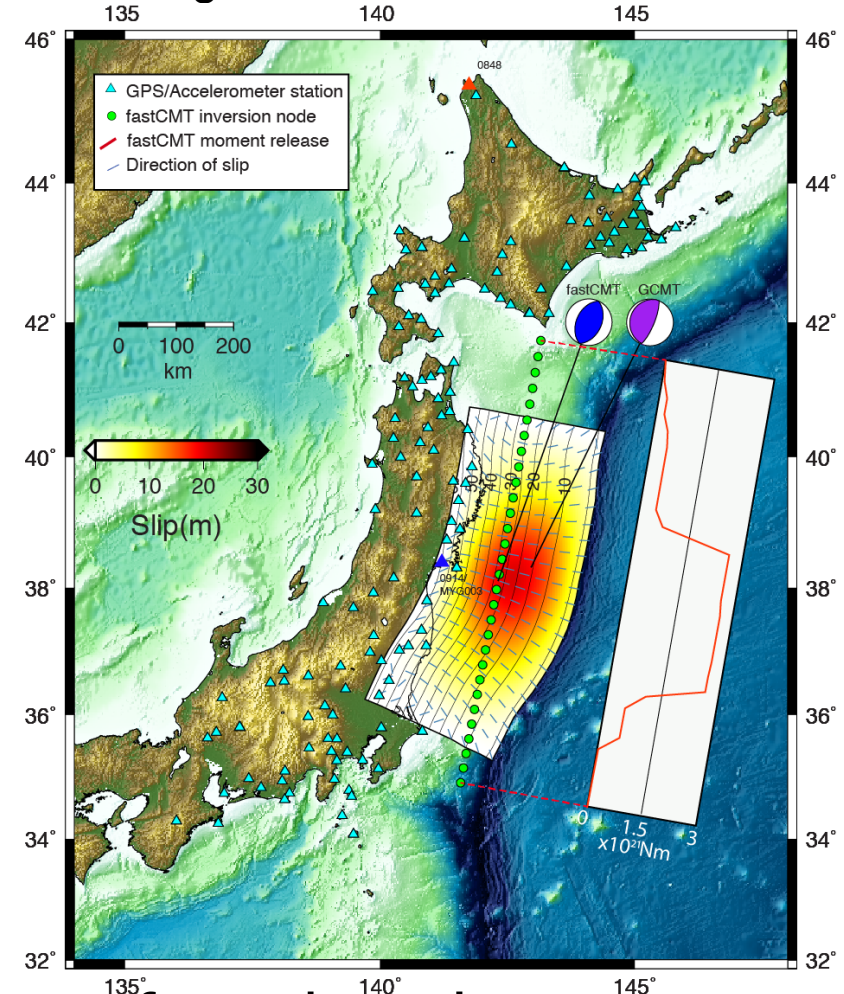
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VII Kogota	20k
VII Rifu	35k
VI Ofunato	35k
VI Sendai	1,038k
VI Yamagata	255k
V Morioka	295k
V Fukushima	294k
IV Utsunomiya	450k

bold cities appear on map (k = x1000)

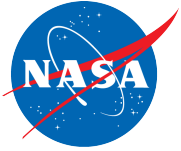
Event ID: usc0001xgp

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty. <http://earthquake.usgs.gov/pager>

M 9 at 2.6 minutes
Seismogeodetic – extended source



Seismogeodetic data provides
better estimates of finite extent of earthquake



Technology Demonstration – Earthquake and Tsunami Hazards

M 8.9 at 2.5 hours
Traditional seismic – extended source

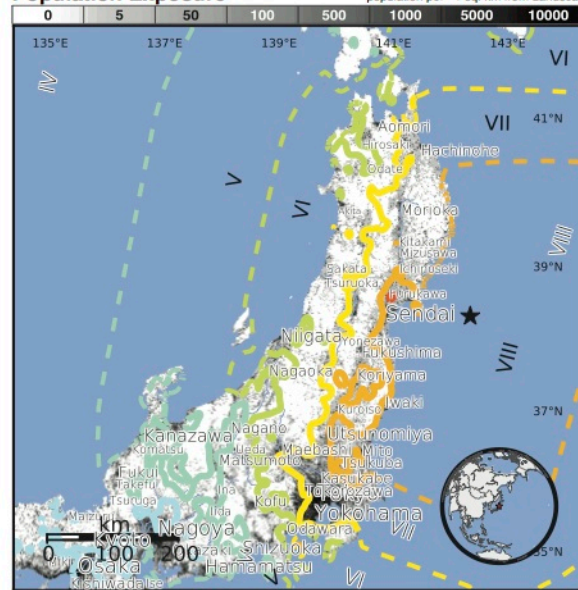
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Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

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1994-12-28	263	7.7	VII(132k)		3
1983-05-26	369	7.7	VII(174k)		104

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides, and fires that might have contributed to losses.

Selected City Exposure

from GeoNames.org

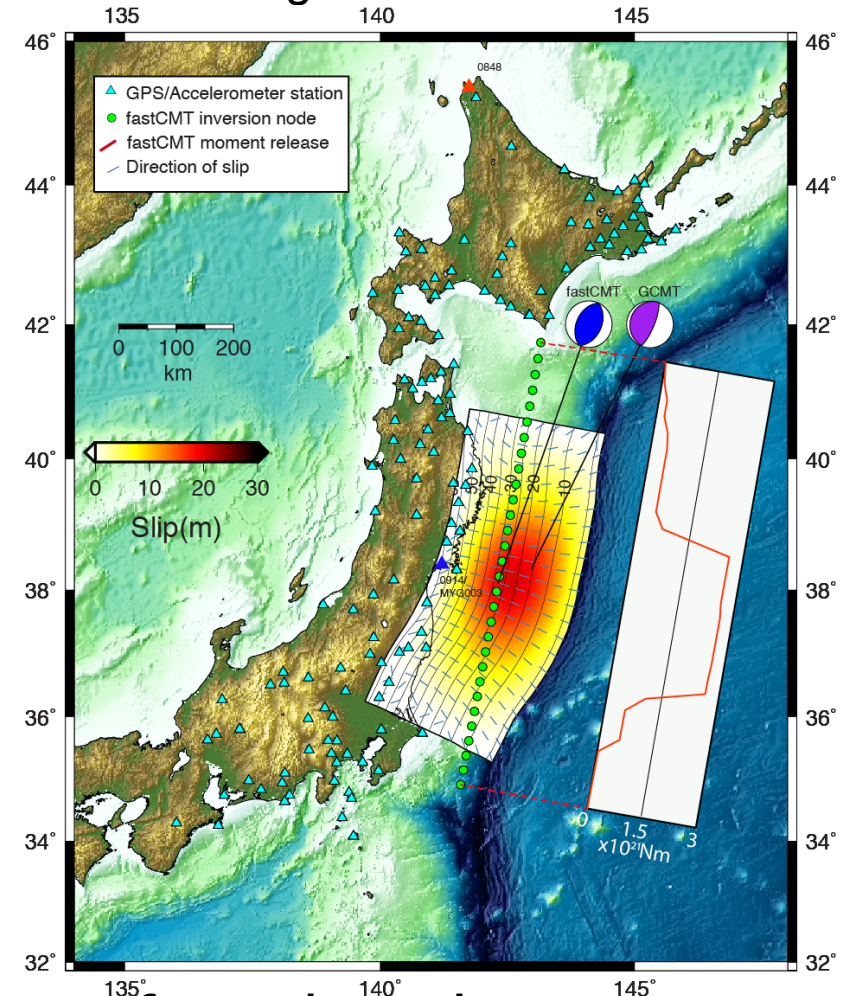
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bold cities appear on map

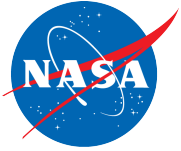
(k = x1000)

Event ID: usc0001xgp

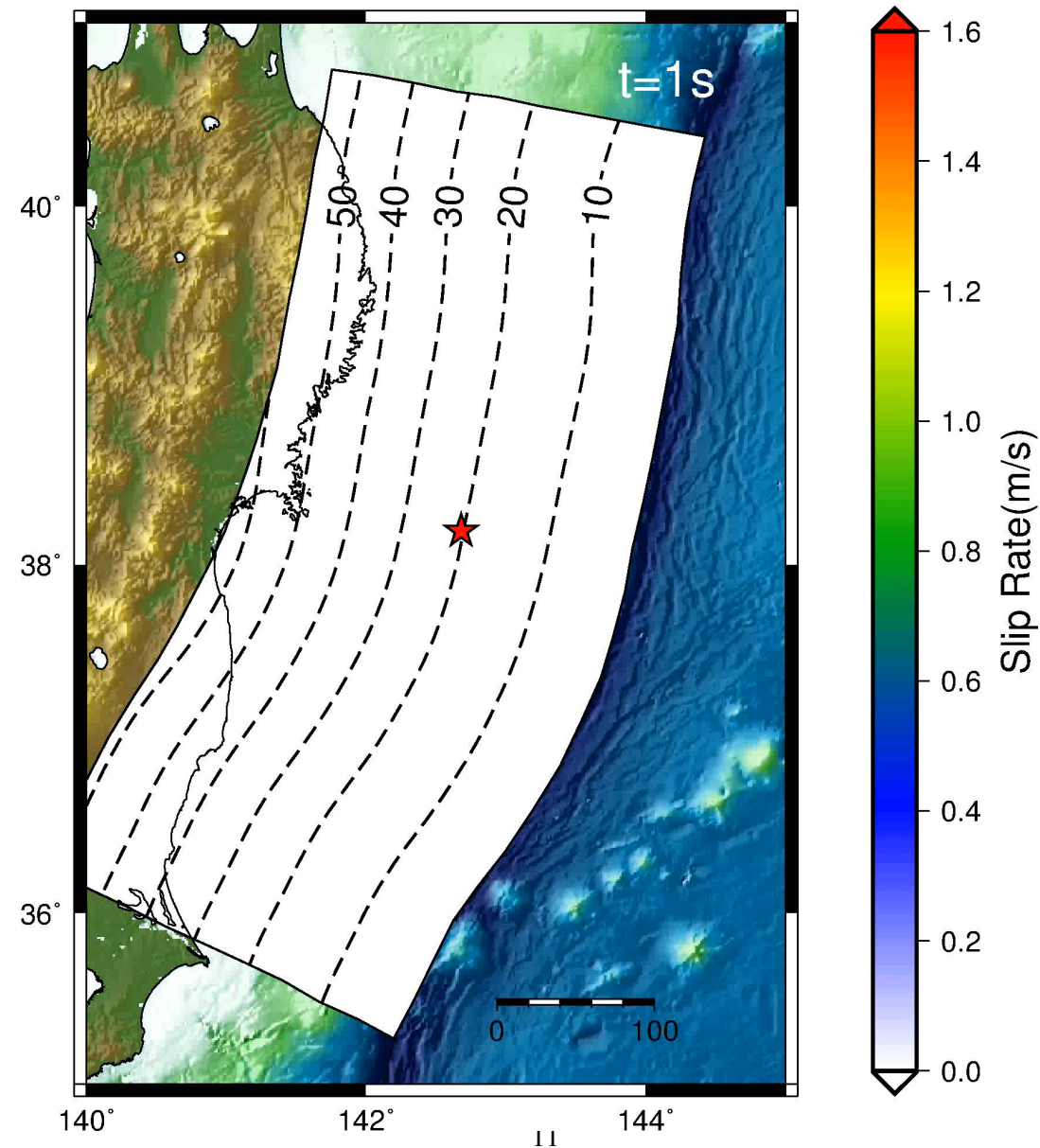
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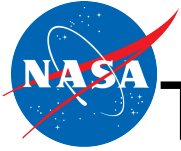


Seismogeodetic data provides better estimates of finite extent of earthquake

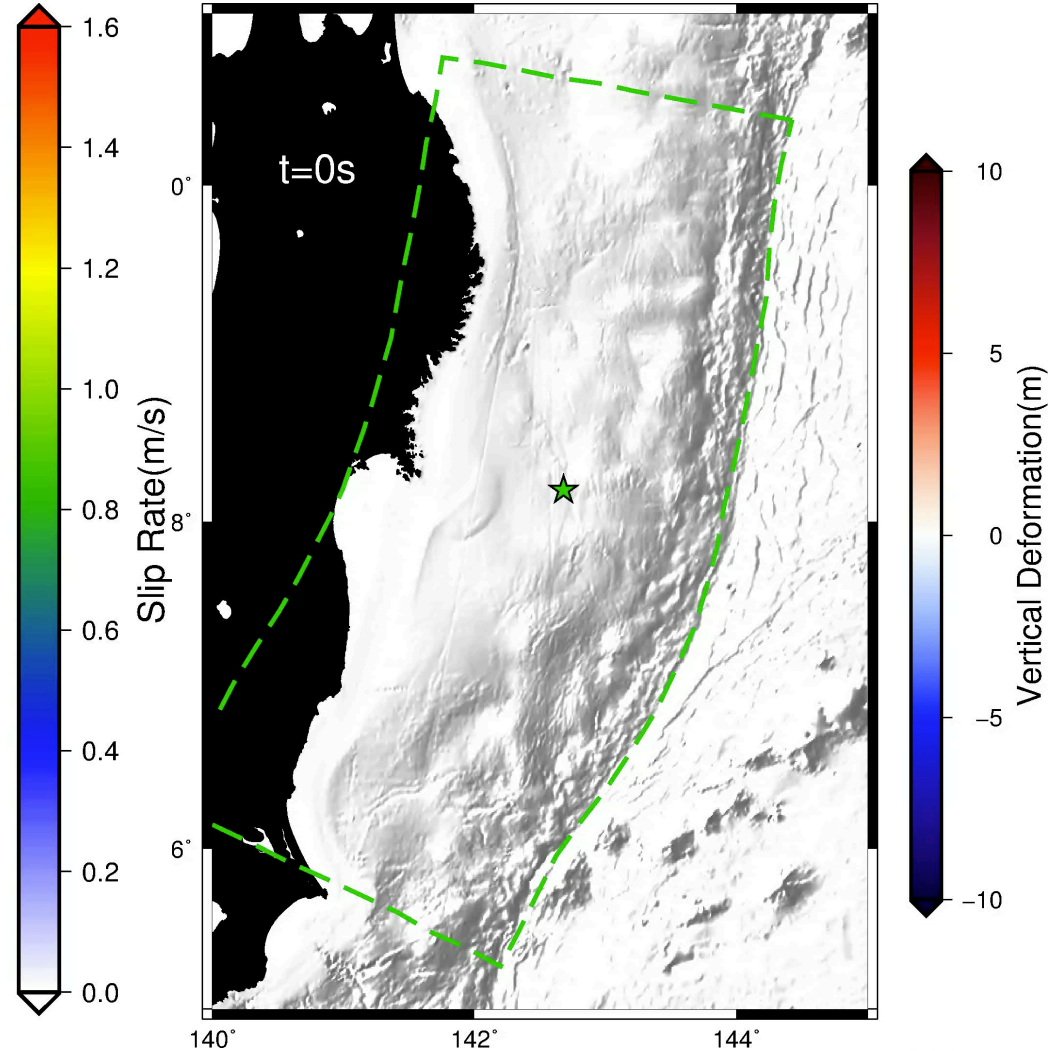
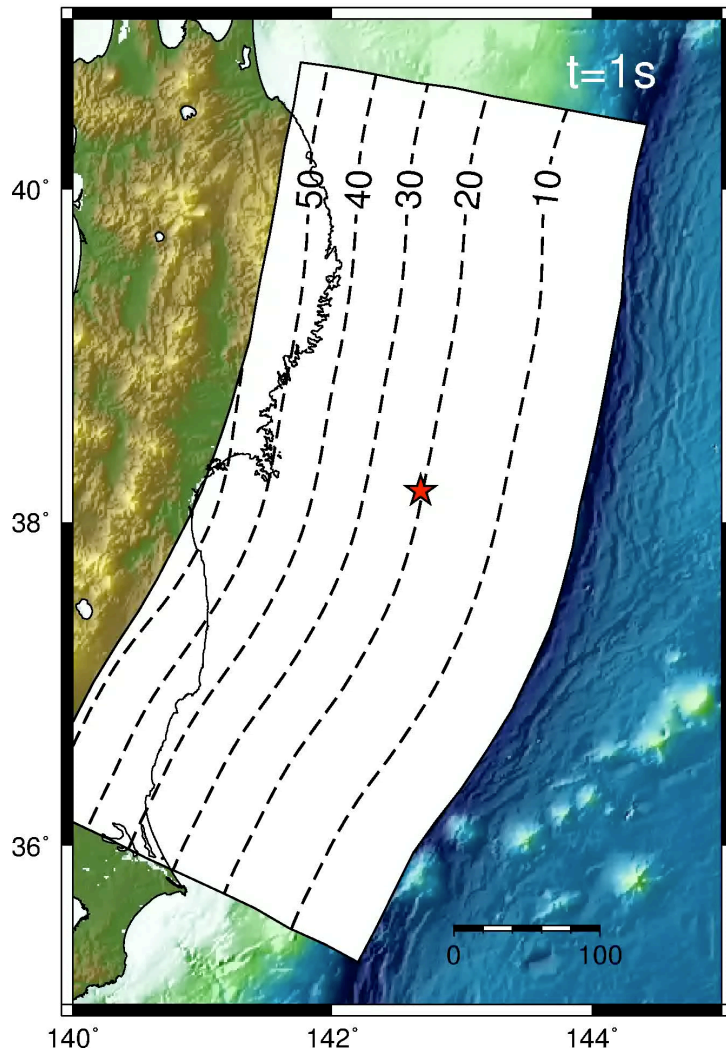


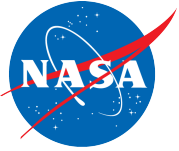
Technology Demonstration – Kinematic Source Inversion



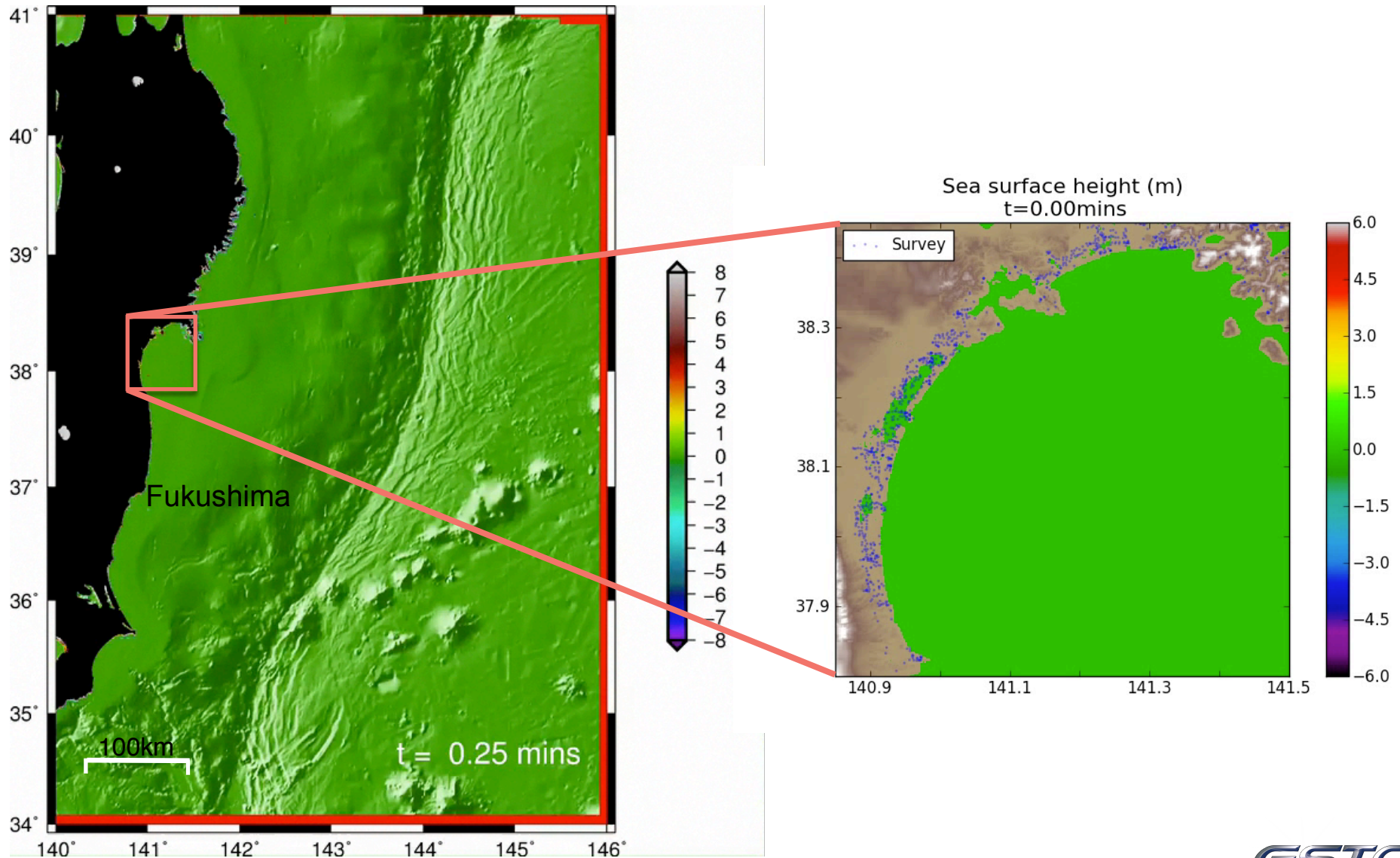


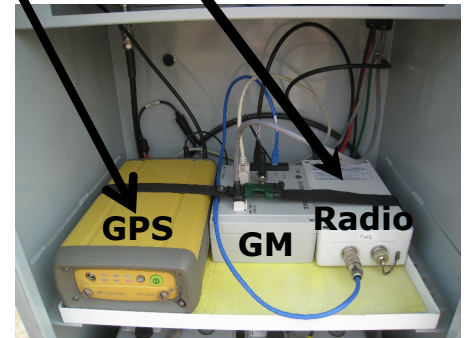
Time dependent deformation of the seafloor

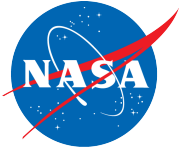




Inundation prediction compared to post-event land survey

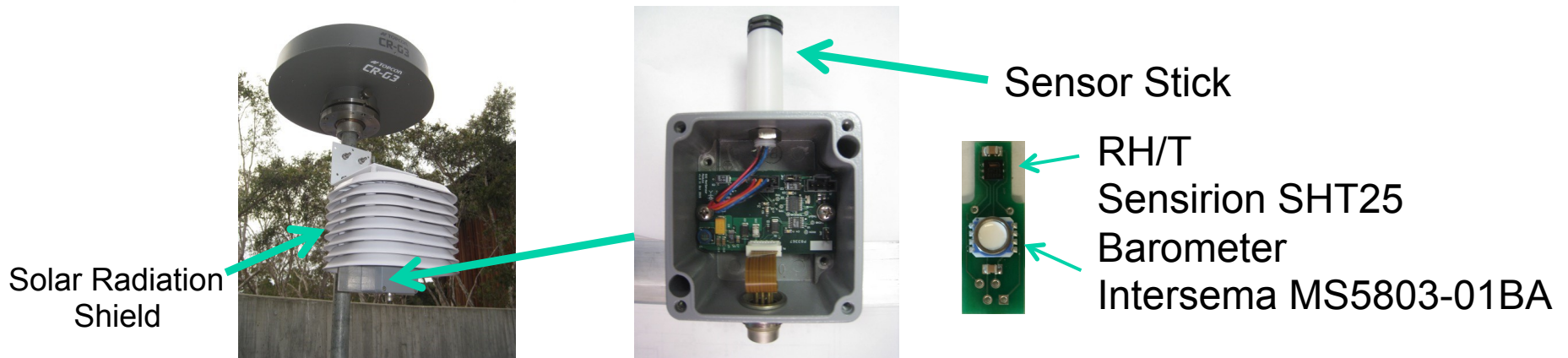




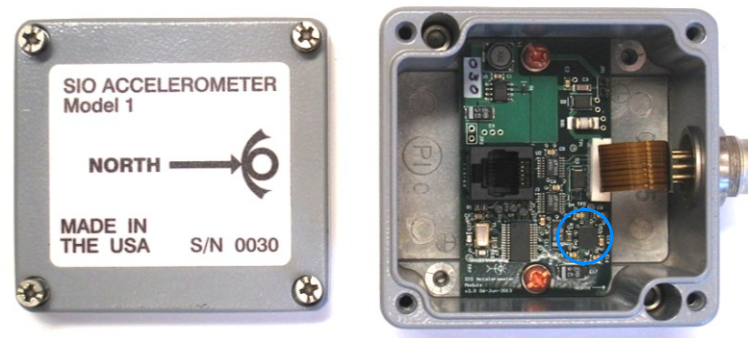


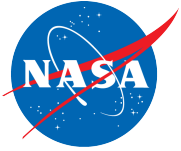
Sensor technology: Real-time autonomous sensor web

SIO MEMS Met Package

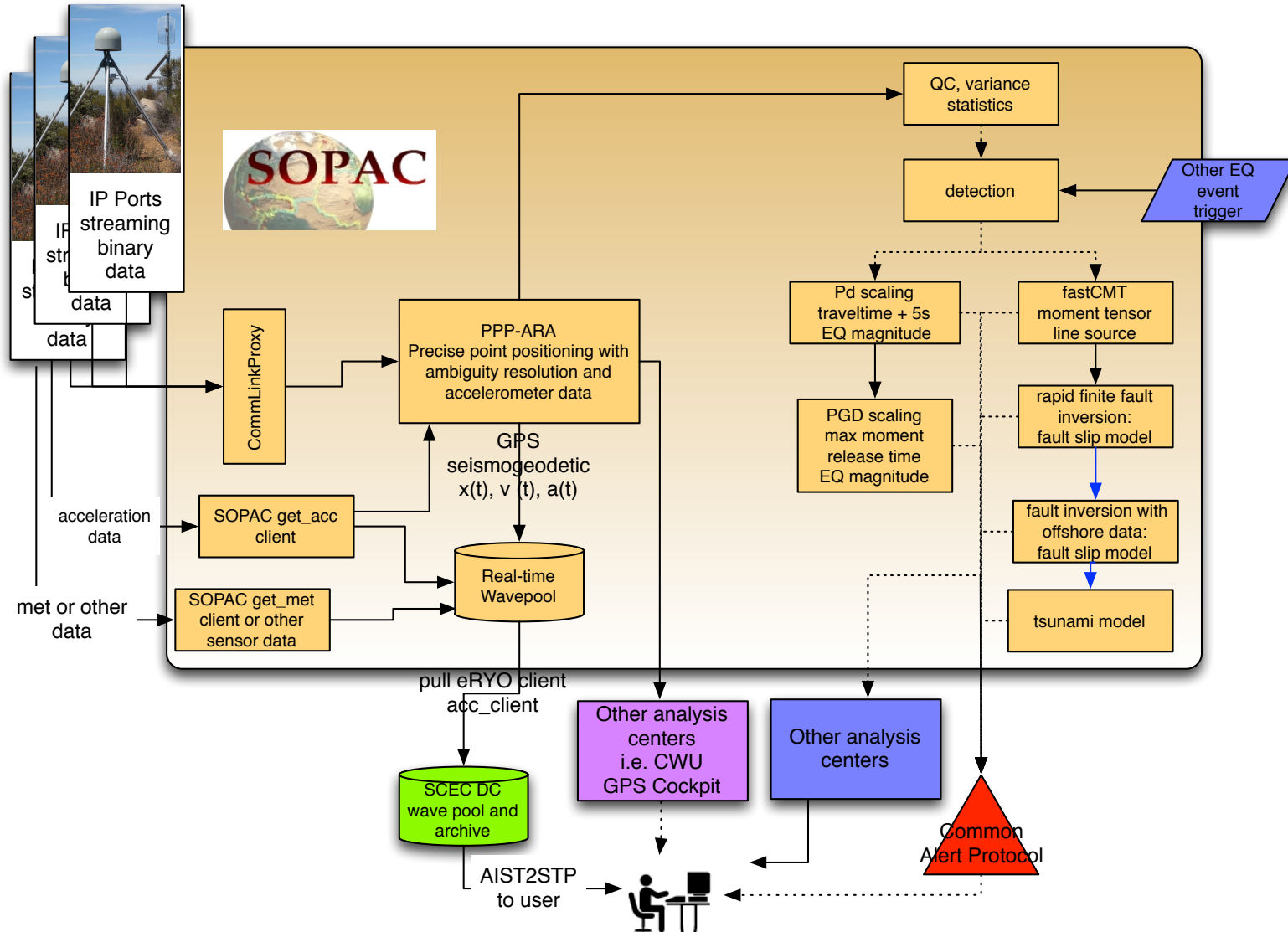


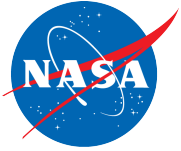
SIO Accelerometer Package 1.0 with 12-bit MEMS accelerometer. Version 2.0 will include a 16-bit MEMS accelerometer.





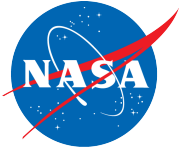
Information technology: Real-time analysis and exporting natural hazard products to users





AIST demonstration

- Example 1: Building monitoring
 - technology development and testing
 - 4 story structure on NSF Network for Earthquake Engineering Simulation (NEES) shaketable
- Example 2: Earthquake hazard
 - technology implementation
 - 10 June 2016 Mw 5.2 Borrego Springs Earthquake
- Example 3: Building monitoring in the field
 - technology implementation for public/private projects
 - 3 story structure in Mexicali
- Example 4: Flash flood hazard
 - 19 July 2013 Southern California monsoon thunderstorms and flash floods



Technology development and testing

Comparison of SIO MEMS and observatory-grade accelerometers under conditions of large-amplitude shaking.

Earthquake simulations based on the 1979 M_w 6.6 Imperial Valley (PGA 0.52g) & 1989 M_w 6.9 Loma Prieta events (PGA 0.57g)



Collocated foundation instruments

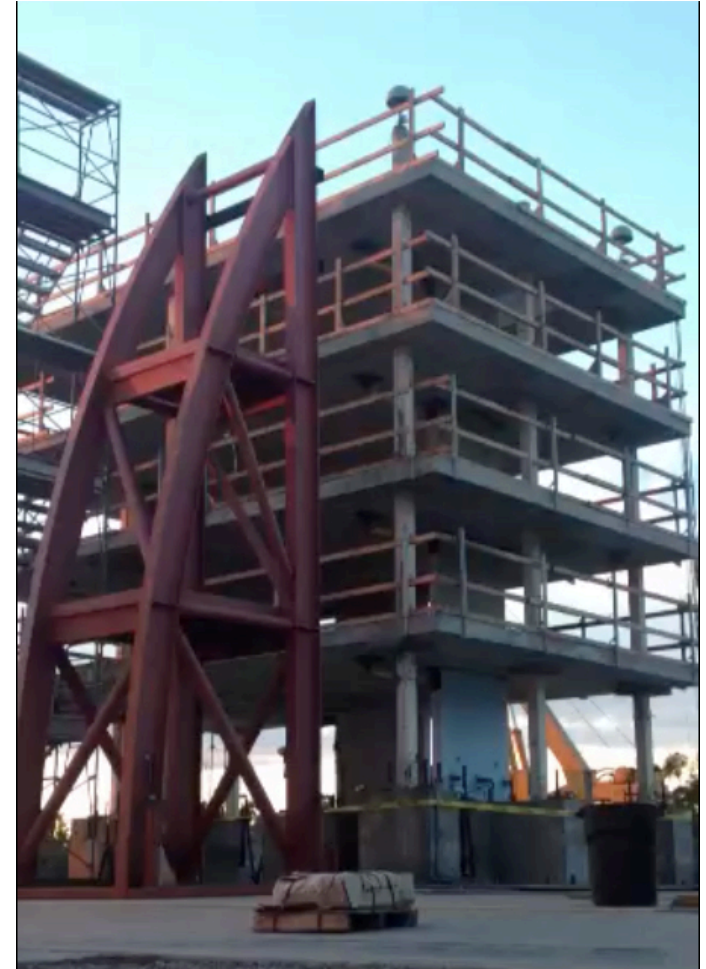
GNSS antenna

Recorded 10 Hz GPS observations.

SIO GAP containing MEMS accelerometer

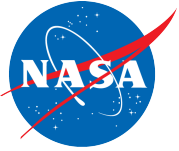
Kinometrics EpiSensor accelerometer

Both recorded at 100 Hz.

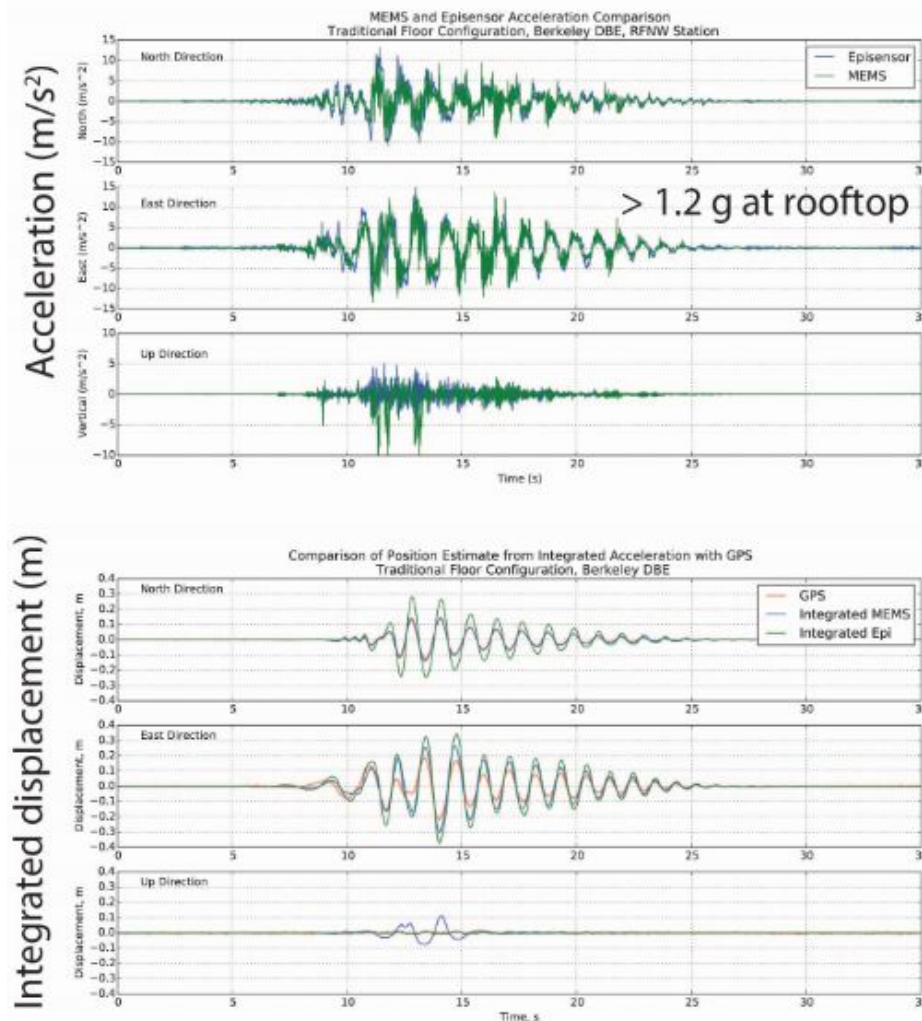


UC San Diego Large High-Performance Outdoor Shake Table (LHPOST)



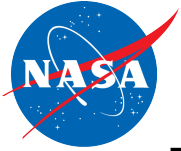


2013-14 Shake Table Tests: Comparison of SIO MEMS and High-End Accelerometers



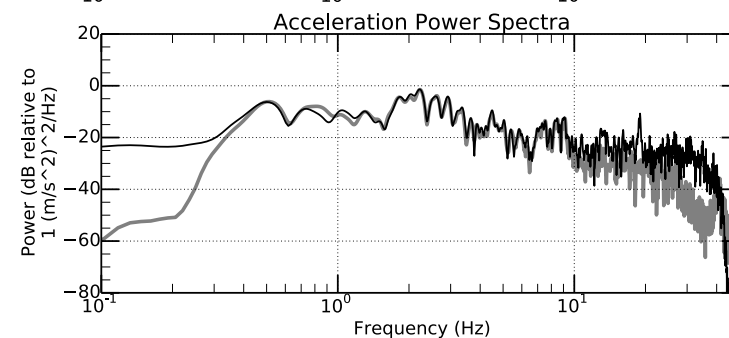
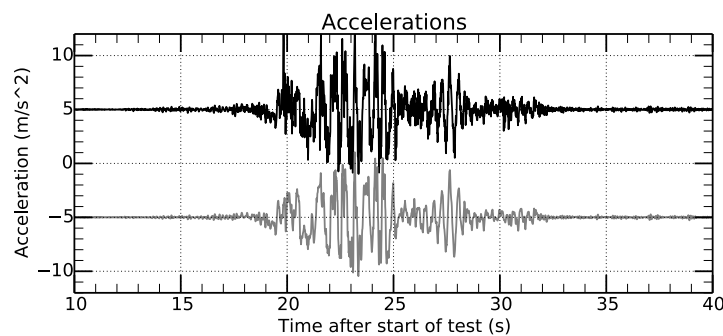
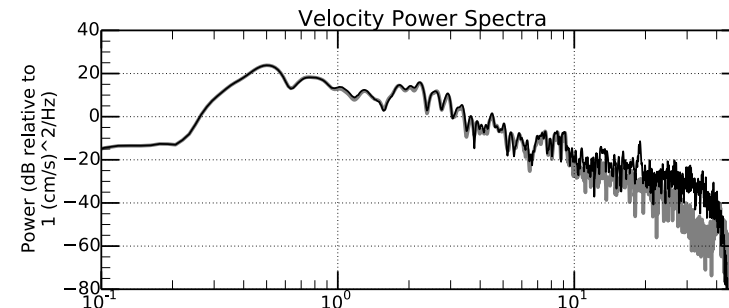
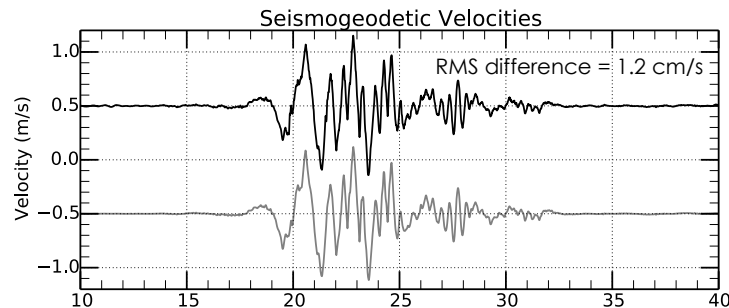
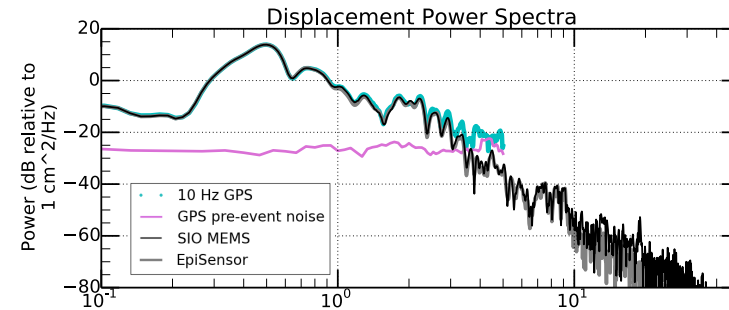
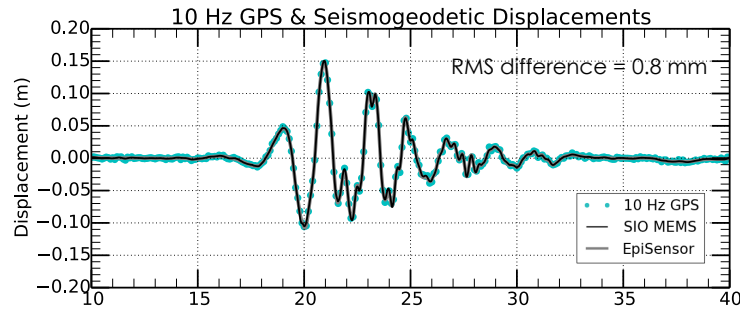
Serves the earthquake engineering and structural design community

- Enable monitoring of structures at lower cost
- Detect permanent damage
- 1.5% interstory drift defines building failure criterion
- Assesses building rotation



Technology development and testing

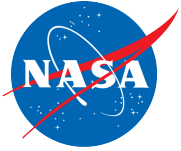
Demonstrate performance over BROAD frequency range



RMS differences between Foundation East component seismogeodetic solutions for all LHPOST earthquake tests:

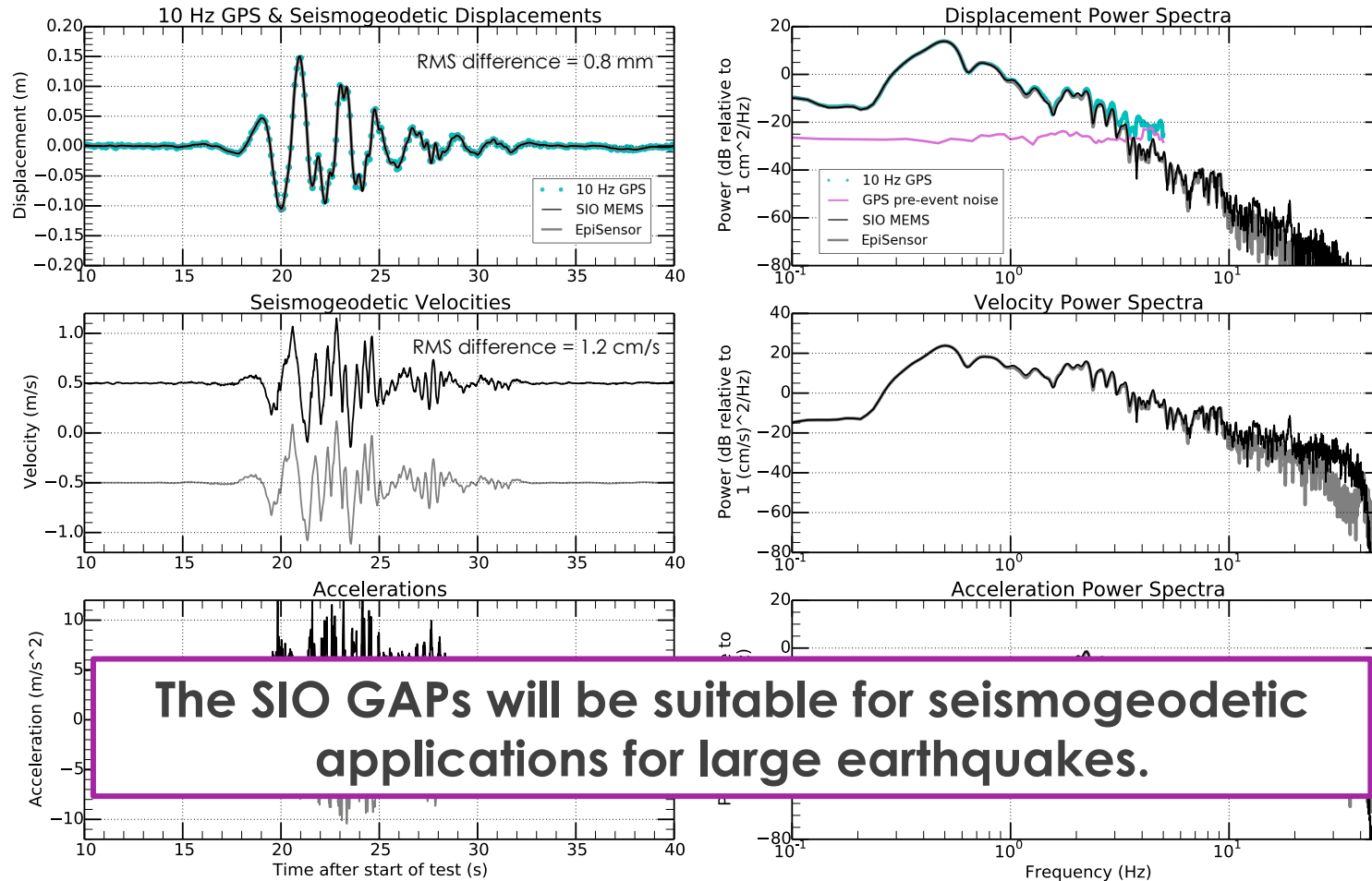
Displacements: $1.3 \pm 0.8 \text{ mm}$

Velocities: $1.0 \pm 0.4 \text{ cm/s}$



Technology development and testing

Assessing the performance of the MEMS accelerometers

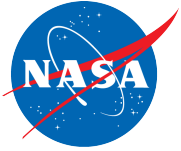


The SIO GAPS will be suitable for seismogeodetic applications for large earthquakes.

RMS differences between Foundation East component seismogeodetic solutions for all LHPOST earthquake tests:

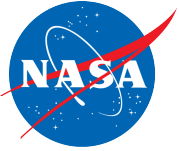
Displacements: 1.3 ± 0.8 mm

Velocities: 1.0 ± 0.4 cm/s

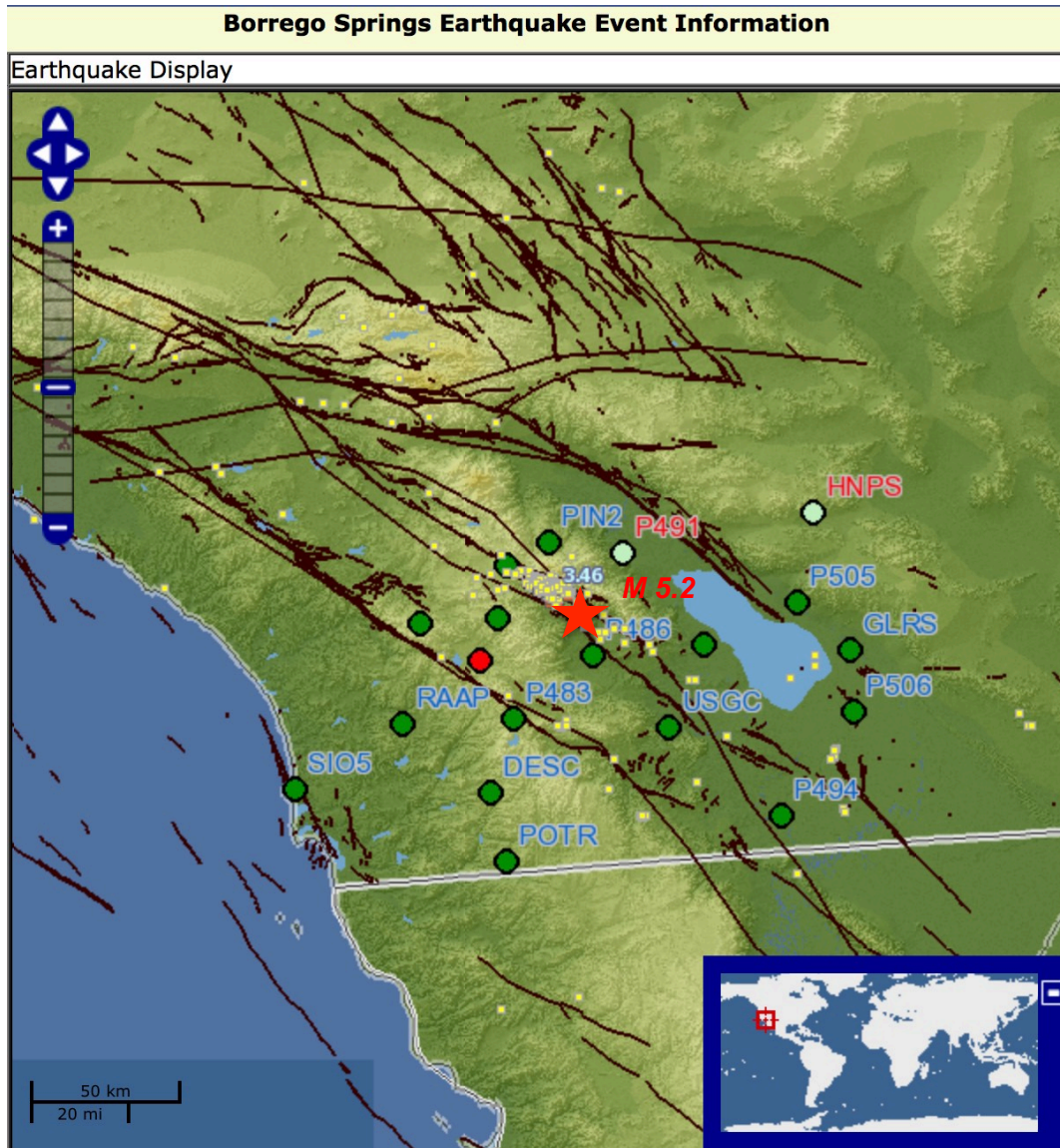


AIST demonstration

- Example 1: Building monitoring
 - technology development and testing
 - 4 story structure on NSF Network for Earthquake Engineering Simulation (NEES) shaketable
- Example 2: Earthquake hazard
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 - 10 June 2016 Mw 5.2 Borrego Springs Earthquake
- Example 3: Building monitoring in the field
 - technology implementation for public/private projects
 - 3 story structure in Mexicali
- Example 4: Flash flood hazard
 - 19 July 2013 Southern California monsoon thunderstorms and flash floods



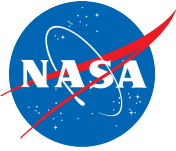
Technology Implementation – San Andreas Fault



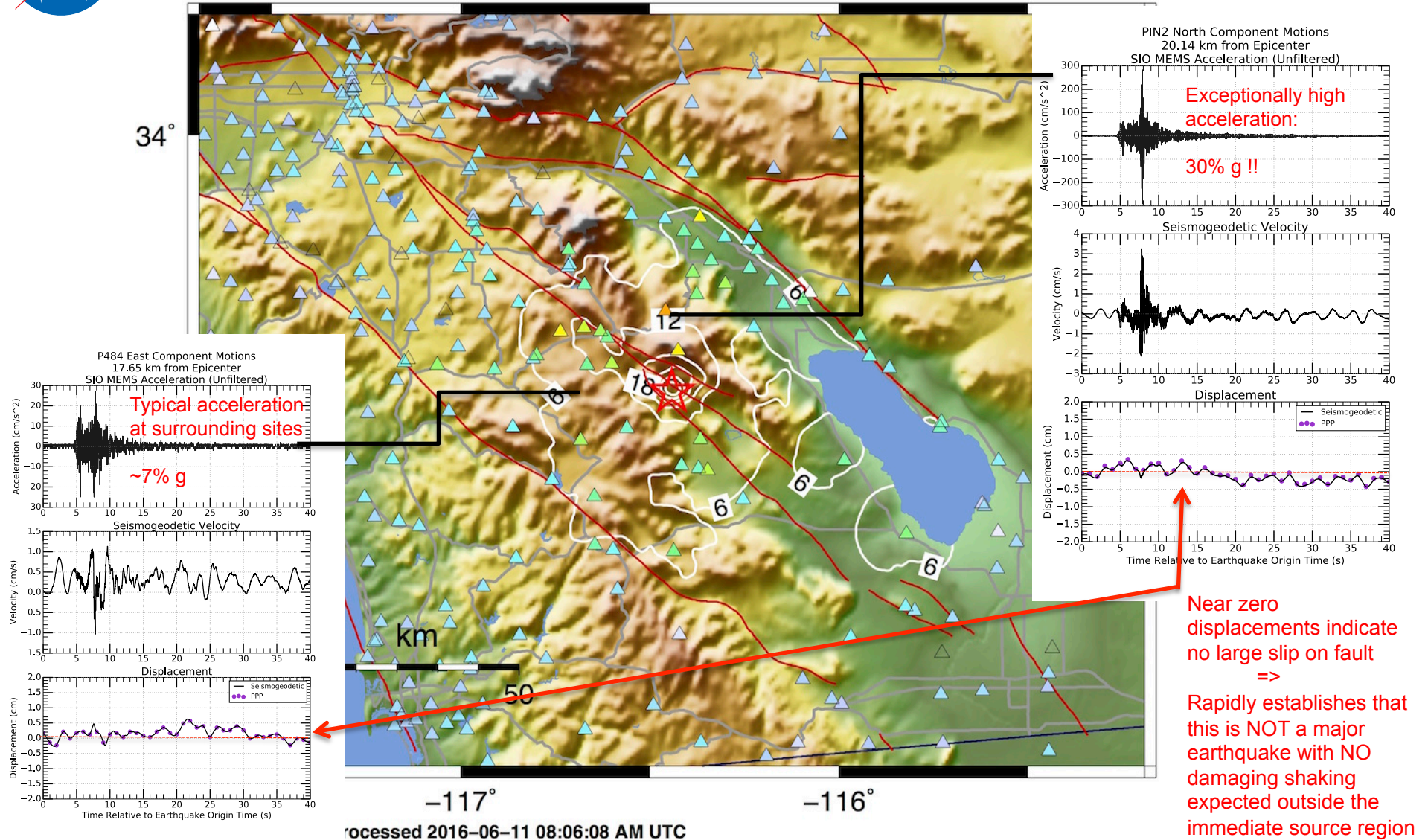
22% probability of an earthquake with $M > 6.5$ in 30 years on the Coachella Segment of the San Andreas Fault (UCERF V3, 2014)

SIO Geodetic Modules and Accelerometer Packages have been operating at 17 stations in southern California.

Captured 10 June 2016 Mw 5.2 Borrego Springs earthquake.

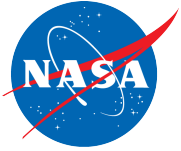


Real-time observations of Mw 5.2 earthquake



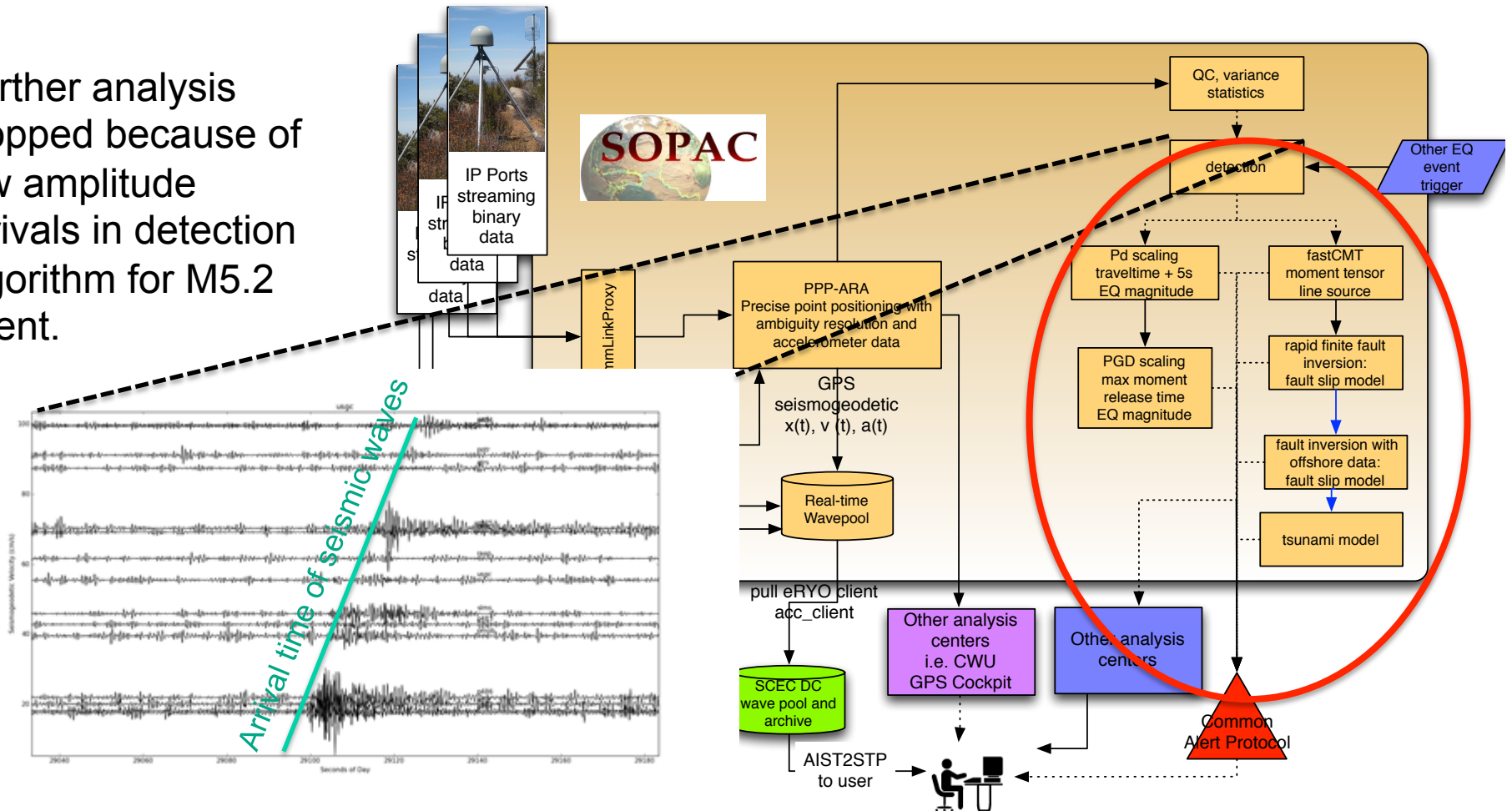
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

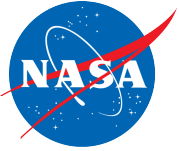


Demonstrate advanced warning products: earthquake detection

Further analysis stopped because of low amplitude arrivals in detection algorithm for M5.2 event.

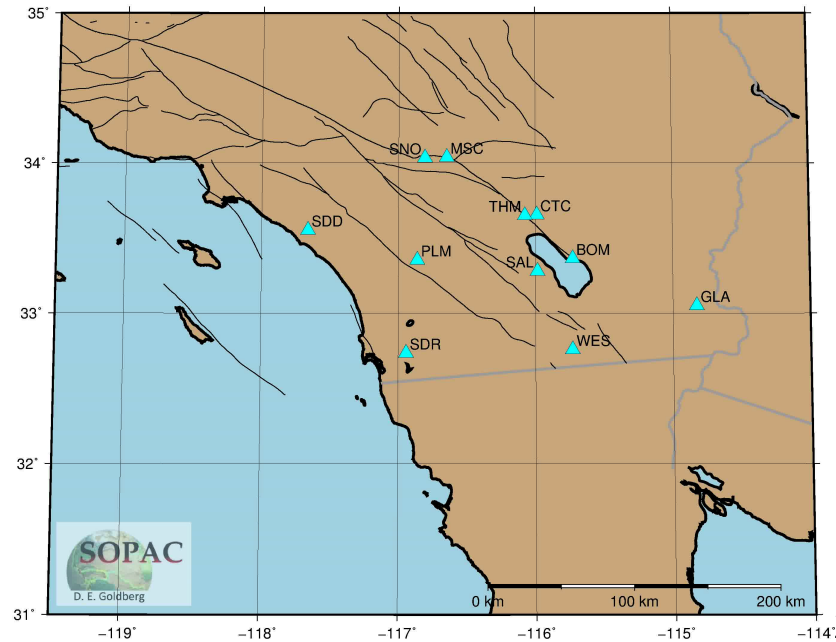
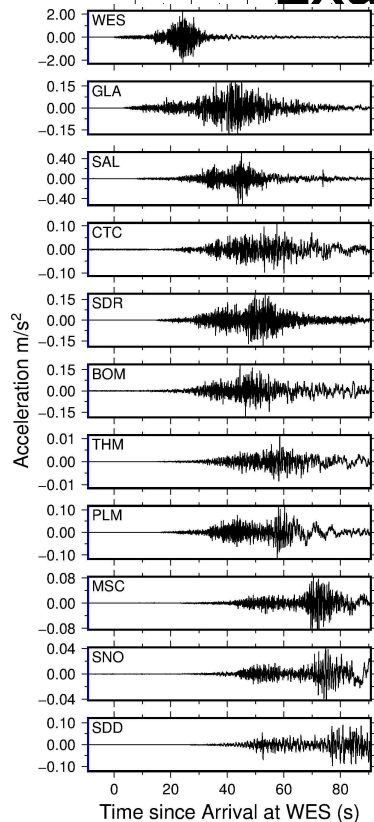


Automated real-time generation of higher level products is therefore tested with past earthquake data.



Demonstrate advanced warning products: Earthquake detection & location

Example from 2010 Mw 7.2 El Mayor-Cucapah



Simulated real-time analysis for the 2010 Mw 7.2 El Mayor-Cucapah earthquake in northern Baja California, Mexico.

100 Hz GPS+accelerometer seismogeodetic displacement and velocity waveforms were analyzed are shown at left.

The continuous blue vertical line denotes the current epoch.

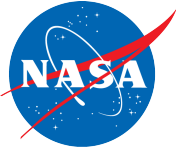
The preceding red lines indicate when the *P* wave was detected at each station.

Once 4 stations have triggered, an estimate of the hypocenter can be made (yellow star).

Red circle: Propagation of *P*-wave triggering detection
Green circle: Propagation of damaging *S*-waves

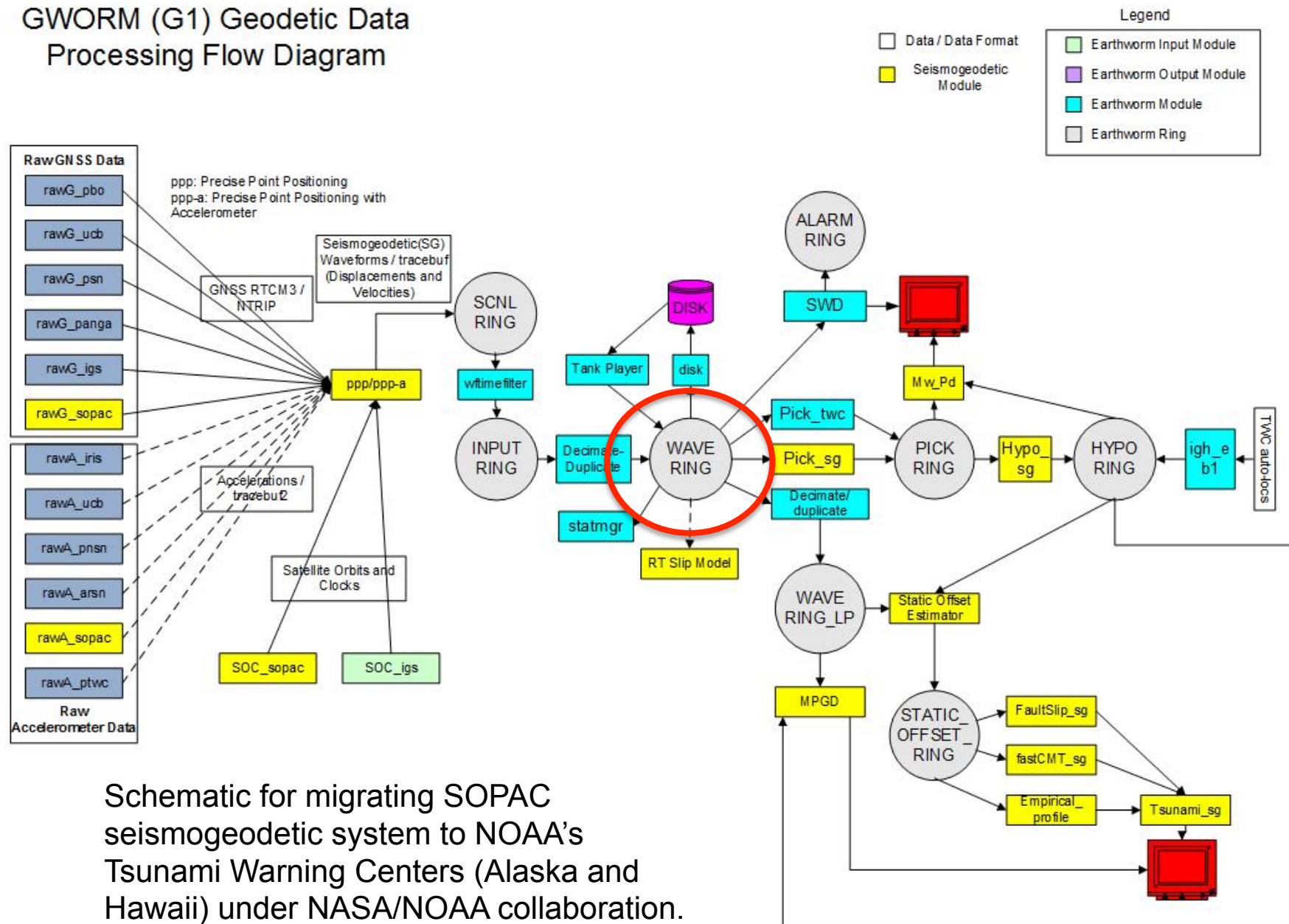
It would take the *S* wave about 80-90 seconds after detection until it arrived in the heavily-populated regions of Riverside and Los Angeles Counties.

Magnitude estimate of Mw 7.2 is determined through peak ground displacement (PGD) magnitude scaling, updated as more information arrives.



Technology Infusion: NOAA Tsunami Early Warning System







GWORM (G1) Geodetic Data Processing Flow Diagram

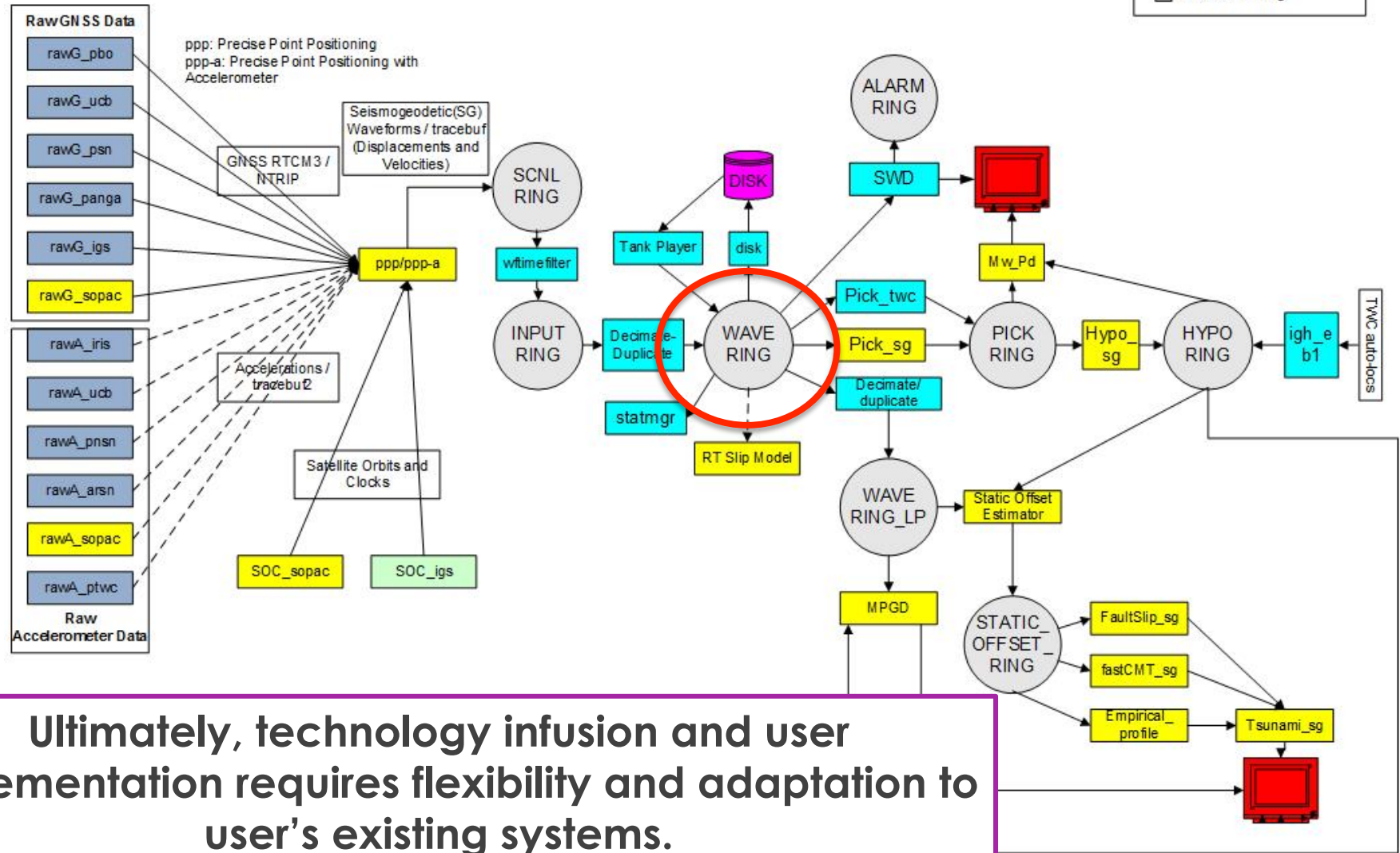


Schematic for migrating SOPAC seismogeodetic system to NOAA's Tsunami Warning Centers (Alaska and Hawaii) under NASA/NOAA collaboration.

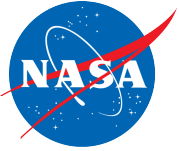


Legend

-  Data / Data Format
-  Seismogeodetic Module
-  Earthworm Input Module
-  Earthworm Output Module
-  Earthworm Module
-  Earthworm Ring

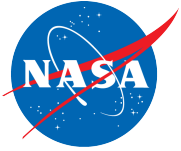


Ultimately, technology infusion and user implementation requires flexibility and adaptation to user's existing systems.



AIST demonstration

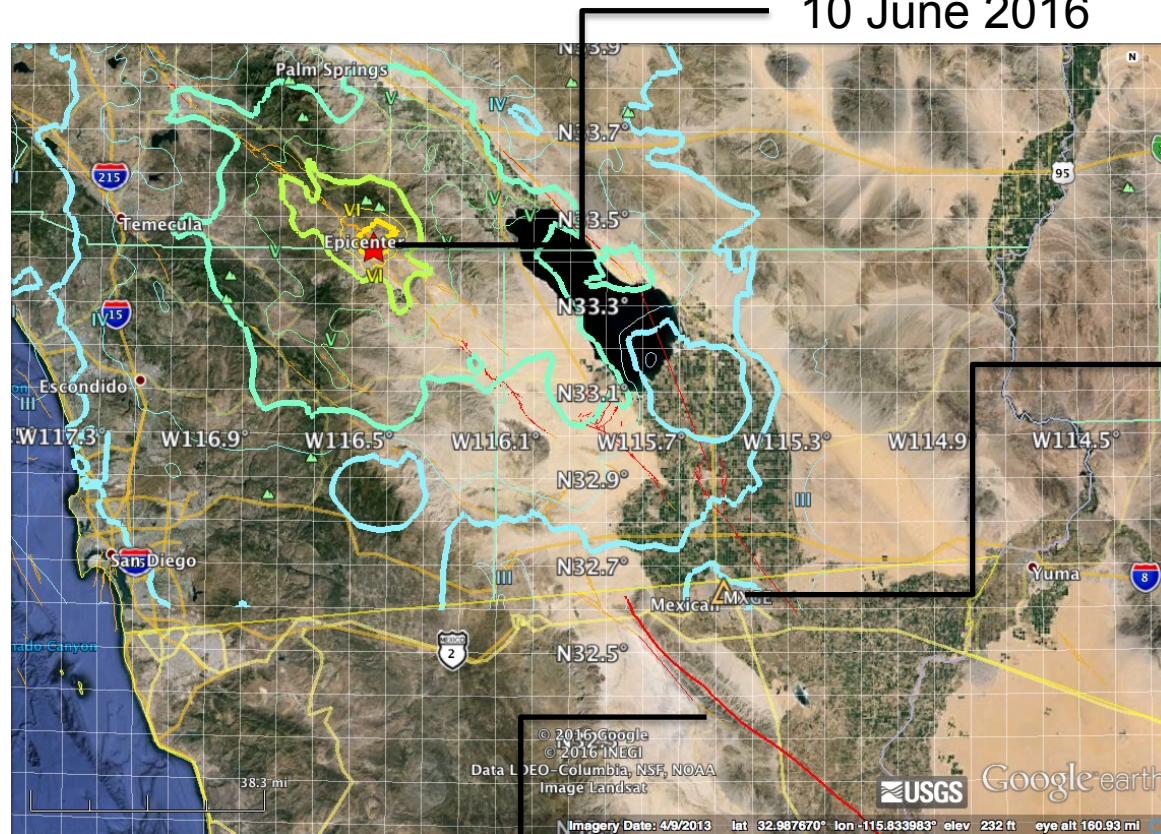
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Structural Monitoring in the Field

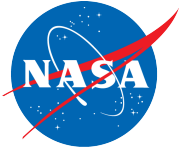
- To demonstrate a building responds to earthquakes safely and as expected using the real-time GPS-seismic monitoring system

M 5.2 Borrego Springs Earthquake
10 June 2016



Mexicali
Building
Monitoring
Site

M 7.2 El Mayor Cucapah Earthquake
4 April 2010

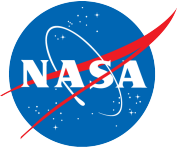


Seismogeodetic system installation



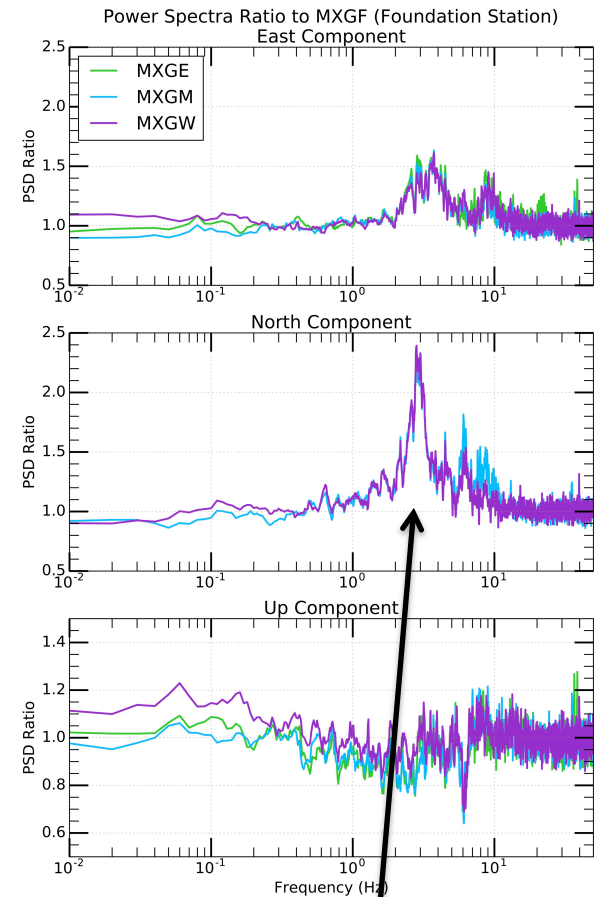
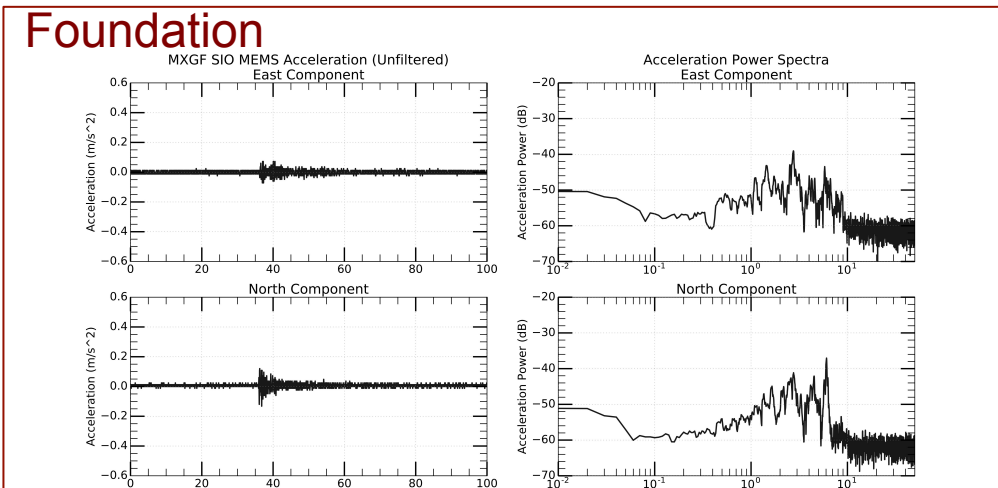
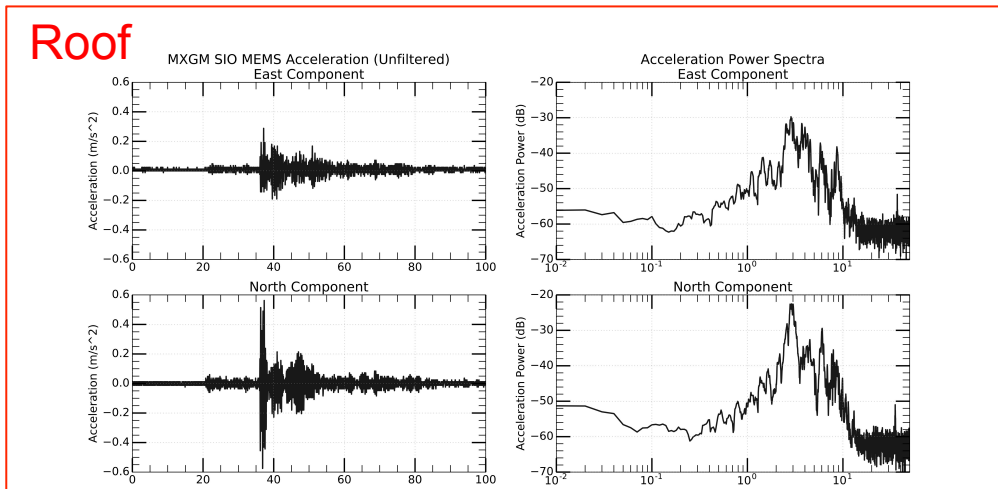
MXS1 reference site



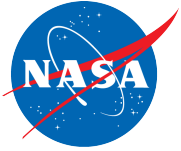


Amplification of structure

- Access to monitoring information provides rapid assessment of building safety after M5.2 earthquake

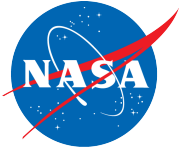


Motions amplified by ~60% in
N-S component
(shorter building dimension)

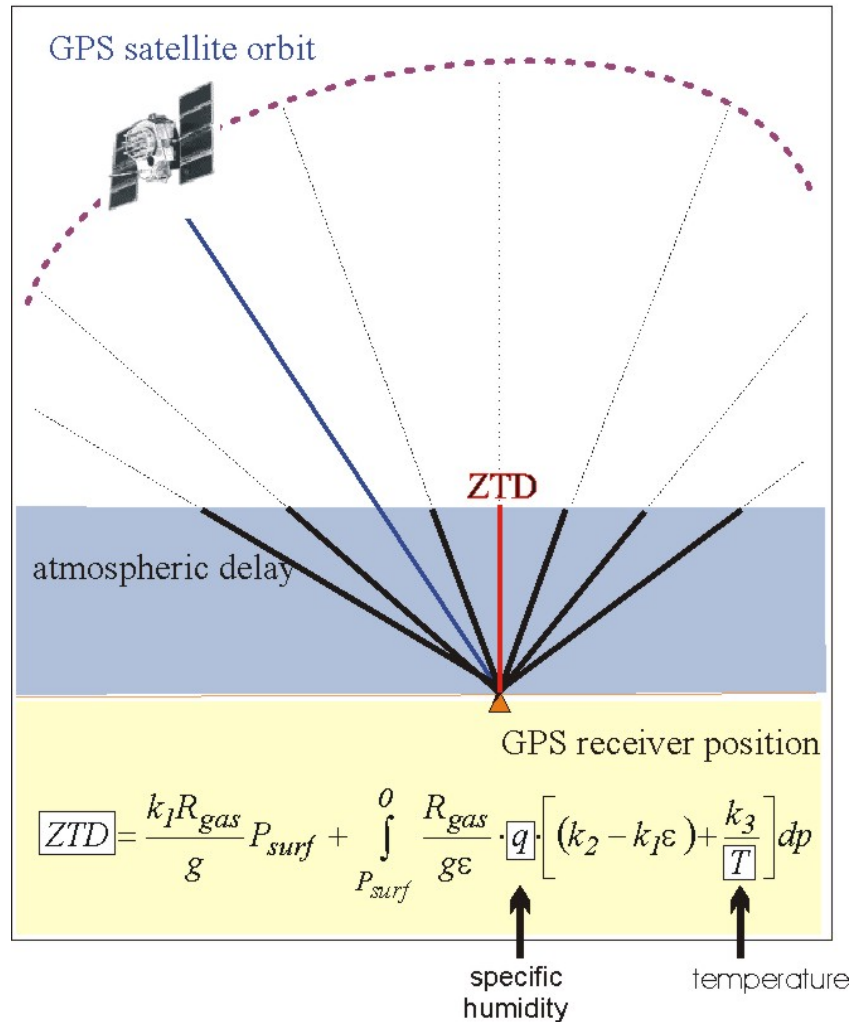


AIST demonstration

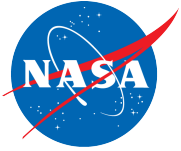
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Technology Demonstration – Extreme Weather Hazards



- Signals from the GPS satellites are affected by moist air
- Position measurement requires estimating delay through atmosphere
- Automatically generate derived atmospheric water vapor above site.
- Disseminate this to NWS partners.



Technology Demonstration – Extreme Weather Hazards



Station SIO5 in La Jolla upgraded with SIO GAM

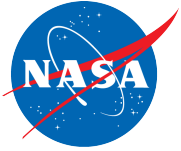
- Geodetic Module
- MEMS Accelerometer Package
- MEMS Meteorological Package

A high-end Vaisala WXT-510 Multi-Weather Sensor has been deployed for comparison with the less expensive SIO met package.

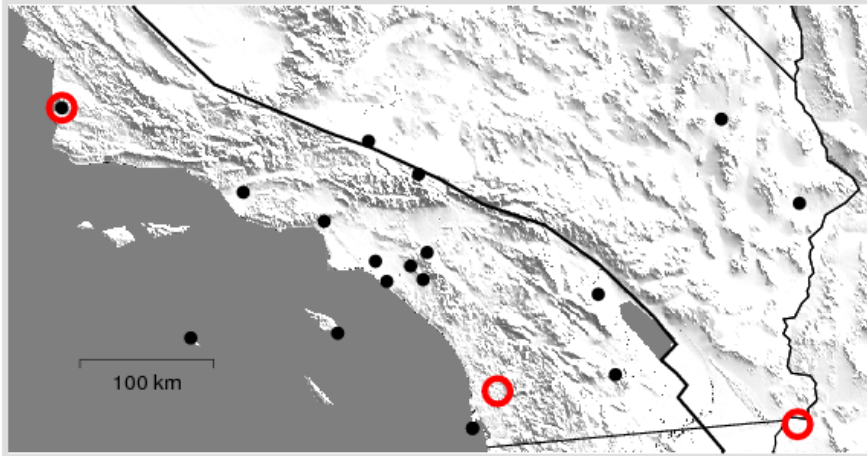
Continuously streamed to SIO

- 1 Hz GPS
- 100 Hz accelerometer data
- 10 s pressure, temperature and relative humidity data are being

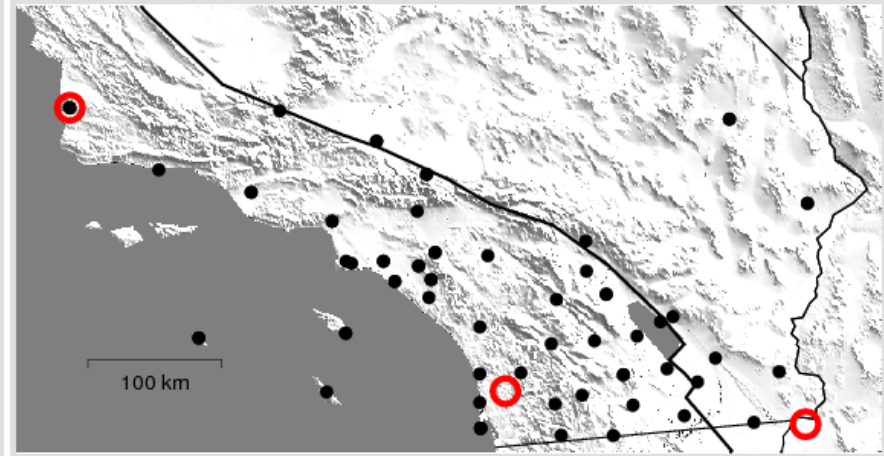
The GPS and met data provide estimates of precipitable water above that location.



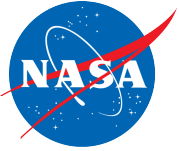
Technology Implementation – Augmentation of NOAA monitoring sites



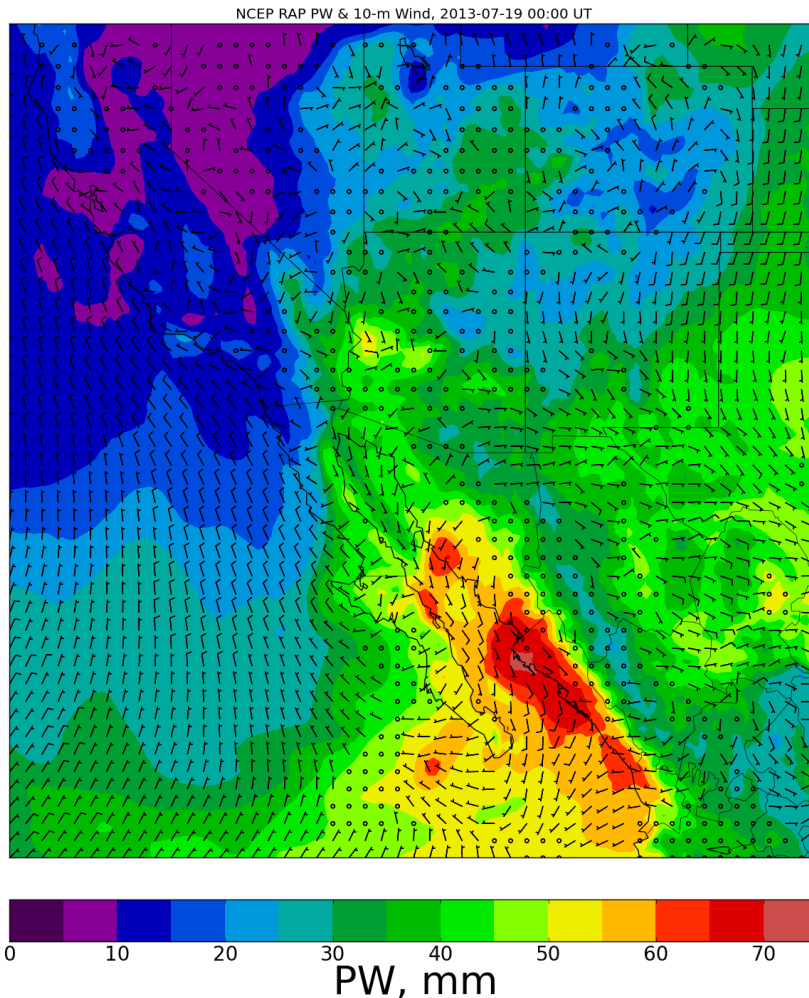
- Southern California stations analyzed by the NOAA GPS-Met project prior to the start of this AIST project.



- The station set including 37 additional stations following the implementation of AIST. Red circles indicate radiosonde sites

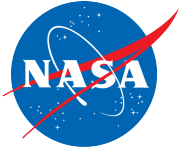


North American Monsoon Event

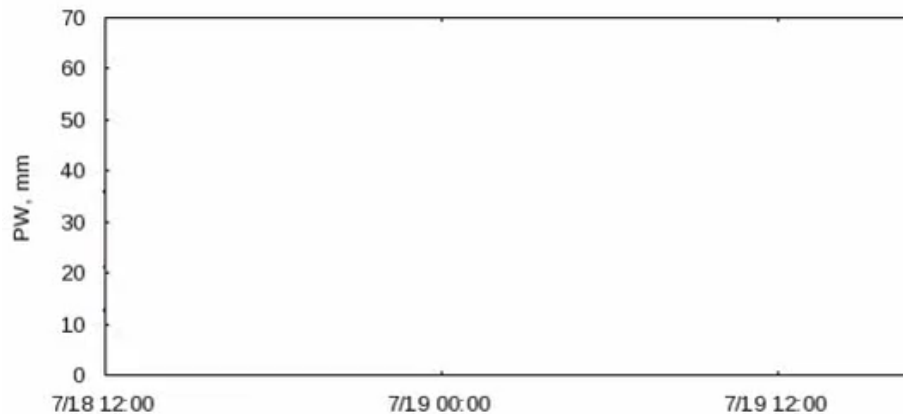
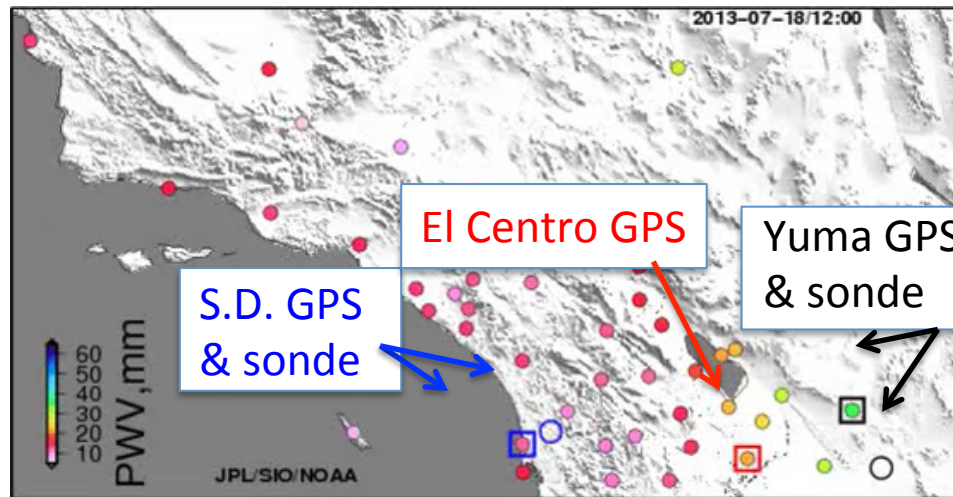


- NCEP Rapid Refresh model precipitable water with 10m winds on 19 July 2013 illustrating monsoonal moisture surge from the Gulf of California

NCEP – NOAA National Center for Environmental Prediction



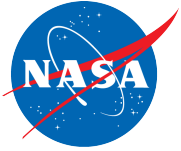
July 2013 Monsoon Event: Successful Flash Flood Warning



Forecaster remarks from NWS Weather Forecast Office in San Diego

“Realtime GPS precipitable water estimates were trending higher over eastern portions of the forecast area... a flash flood watch will be needed for Saturday”

“In order to see the character of the precipitable water values between Yuma and San Diego in the absence of a morning Yuma sounding, the GPS meteorology data was utilized.”



July 2013 Monsoon Event: Successful Flash Flood Warning



Flooding across Highway 78 in San Diego County, California, 22 Jul 2013.

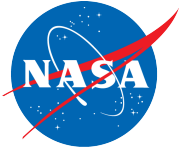
[Photo credit: NOAA]

Storm reports

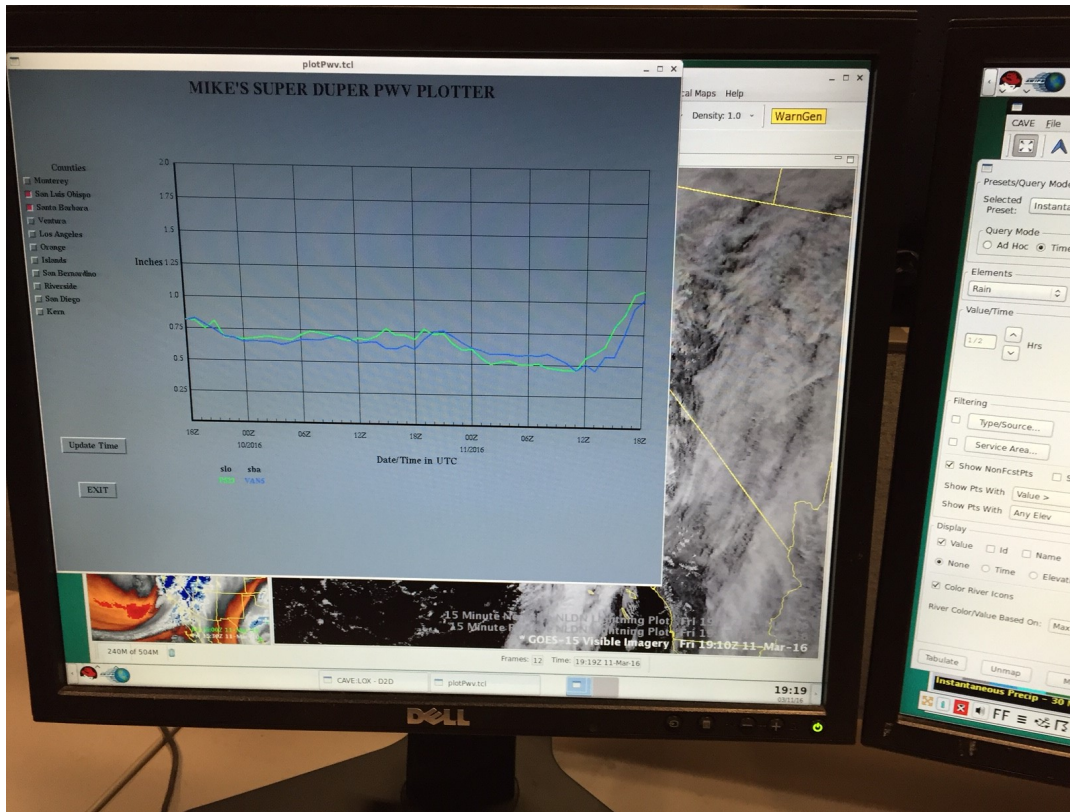
“Highway 78 flooded in two locations at Yacqui Pass with 30 vehicles trapped between the two flooded locations. Many large rocks in the roadway.”

“Battalion Chief flagged down by the public to report debris moving across the roadway on Sunrise Highway”

ESTO
Earth Science Technology Office

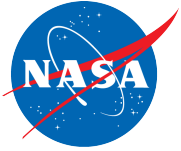


Technology infusion: In-house display of PW data at Los Angeles forecasting office

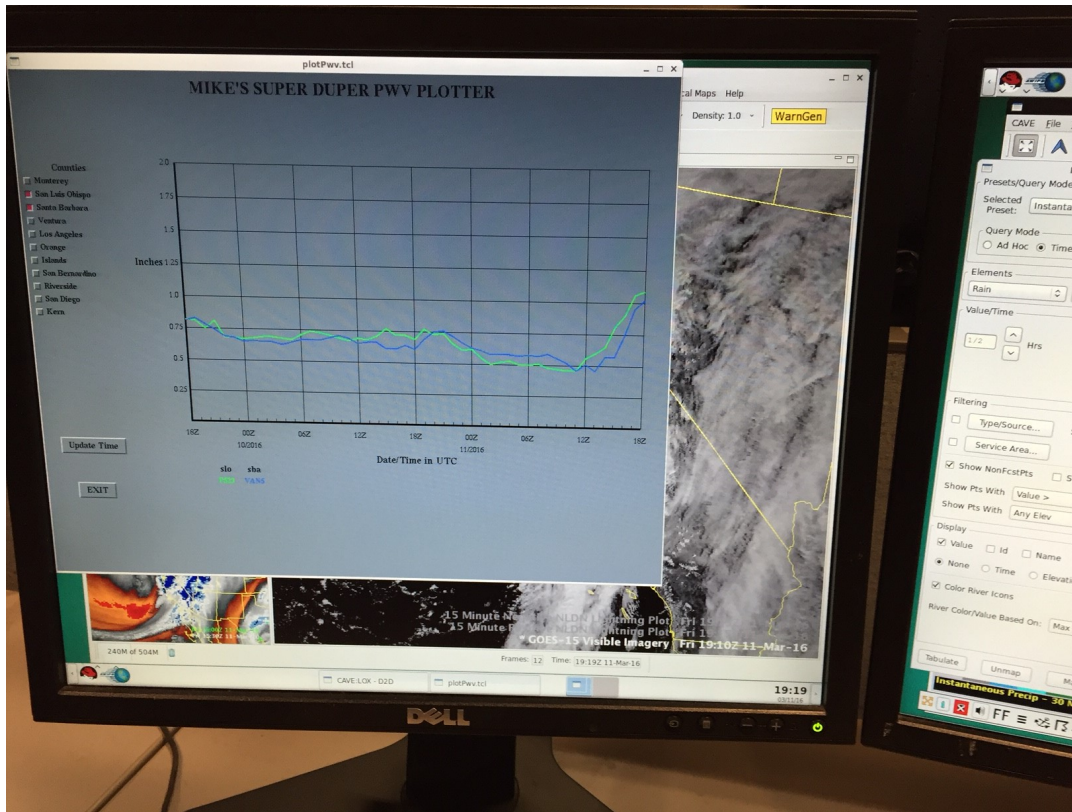


- Initially provided graphical display of GPS PW data through NOAA ESRL
- Local NWS forecasting offices requested direct access after changes in NOAA ESRL support
- Worked with NWS forecasting offices to implement technology.

PW plotter developed by Oxnard office to display data from NOAA's MADIS system. This example shows the increase in PW over a six-hour period at two Santa Barbara stations on March 11, 2016 during a rain event.



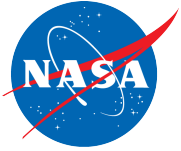
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Ultimately, technology infusion and user implementation requires flexibility and adaptation to user's existing systems.



Conclusions

- Developed a power-efficient, low-cost, plug-in Geodetic Module to interface with MEMS accelerometer, met sensors to expand the range of users of GPS Earth observation data.
- Developed real-time analysis of millimeter-level ground motions and precipitable water and algorithms for rapid calculation of high level products.
- Created a real-time autonomous sensor web to transmit and receive information among regional nodes, including directly to users
- Technology transfer to users continues as part of the technology infusion, for decision support and rapid response to earthquakes, tsunamis, severe storms and flash flooding.

Lessons Learned for AIST

- User base was expanded beyond initial demonstration partners
- More demands for direct access drove IT development as time went on.
- Ultimately, technology infusion and new user implementation requires flexibility and adaptation to user's existing systems.